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Extraterrestrial Surface Construction Technologies

Operations Analysis for Lunar Surface Construction: Results of Two Office of Exploration Case Studies

by
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In an environment of intense competition for Federal funding, the U.S. space research community is responsible for developing a feasible, cost-effective approach to establishing a surface base on the moon to fulfill long-term Government objectives. This report presents the results of a construction operations analysis of two lunar base scenarios provided by the National Aeronautics and Space Administration (NASA). Activities necessary to install the lunar base surface elements are defined and scheduled, based on the productivities and availability of the base resources allocated to the projects depicted in each scenario. The only construction project in which the required project milestones were not completed within the nominal timeframe was the initial startup phase of NASA's *FY89 Lunar Evolution Case Study* (LECS), primarily because this scenario did not include any Earth-based telerobotic site preparation before the arrival of the first crew. The other scenario analyzed, Reference Mission A from NASA's *90-Day Study of the Human Exploration of the Moon and Mars*, did use telerobotic site preparation before the manned phase of the base construction.

Details of the analysis for LECS are provided, including spreadsheets indicating quantities of work and Gantt charts depicting the general schedule for the work. This level of detail is not presented for the scenario based on the 90-Day Study because many of the projects include the same (or similar) surface elements and facilities. The major differences between the two construction efforts are clearly defined in Chapter 4, however.

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FOREWORD

This research was supported by the National Aeronautics and Space Administration (NASA), Office of Exploration, and was managed by the U.S. Army Construction Engineering Research Laboratory (USACERL) under MIPR T-9747P, "Extraterrestrial Surface Construction Technologies." The NASA technical monitor was Barney Roberts, OEXP.

The work was performed by Lisa Y. Bell, KDT Industries, Inc., Austin, Texas, and Walter Boles, Large Scale Programs Institute/The University of Texas at Austin on contract to the Engineering and Materials Division (EM) of USACERL. Alvin Smith was the USACERL contract monitor. Dr. Paul A. Howdyshell is Chief of EM. The USACERL technical editor was Gordon L. Cohen, Information Management Office.

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OPERATIONS ANALYSIS FOR LUNAR SURFACE CONSTRUCTION: RESULTS OF TWO OFFICE OF EXPLORATION CASE STUDIES

1 INTRODUCTION

Background

Future endeavors in space will be shaped by two important aspects of the current space program planning environment: (1) the past two administrations and a majority of the space community have endorsed the concept of permanently manned extraterrestrial surface bases as a long-term objective of the U.S. space program, and (2) the intense competition for Federal funds has fueled a vigorous campaign for improved cost-effectiveness that encourages agency introspection and the formation of new interagency partnerships. The National Aeronautics and Space Administration (NASA) has considerable experience in ground operations for space vehicle assembly, launch operations, and orbit operations, but has limited experience with the challenges of large-scale construction operations. Therefore, it is appropriate for NASA to look to the U.S. Army Corps of Engineers (USACE) for expertise in the areas of construction project management in an effort to find the most cost-effective approach to the construction of extraterrestrial infrastructure. The U.S. Army Construction Engineering Research Laboratory (USACERL) is the Corps' lead agency in research and development for large space structures.

This report represents a joint conceptual planning activity by NASA and USACERL to determine a feasible, cost-effective approach to establishing a surface base on the moon. This study is considered a necessary point of departure for more specific future research in extraterrestrial construction operational analysis.

Objective

This report documents the analysis of lunar base construction scenarios detailed in two NASA studies, the FY89 Lunar Evolution Case Study (LECS) and Reference Mission A of the Office of Exploration 90-Day Study of the Human Exploration of the Moon and Mars. The purpose of this work was to define operational requirements for lunar surface construction, including the identification of related areas that need further study. Specific aspects of the requirements include the characterization of large construction projects as sequences of activities that can be subdivided into more discrete quantities of work. Included in the analysis is the calculation of schedule durations for both missions, and construction resource loading as a function of major program drivers.

Approach

A set of program drivers, or parameters, was defined prior to the study on the basis of past programs and current trends in the development of lunar base scenarios. These parameters were total construction equipment mass (which is often stated as a constraint), mission duration, resource delivery schedule, and selected features of facility design. Many of these parameters were established iteratively throughout the study process, so a major challenge was to define operational requirements parametrically rather than performing a single-point (specific) design. An example is the number of hours associated with site

preparation for the inflatable habitat: this operational requirement was calculated as a function of the habitat diameter (ranging from 10 m to 20 m).

After the parameters were defined, the first task was to assess the broad operational categories of lunar surface construction (e.g., site preparation, materials handling, assembly, site finishing). The resulting information was then used to develop standard operational entities, or "building blocks" (such as excavation, leveling, and utility connections), that could be used to characterize lunar base scenarios. LECS and the 90-Day Study produced scenarios that have been fleshed out in detail sufficient for applying this approach. The design features of surface infrastructure were used to determine the quantity of work to be performed for specific tasks within major construction projects. Resources were then assigned to the tasks to determine the schedule duration of each project. A combination of project management and scheduling software packages and spreadsheets for the microcomputer were used, and customized when necessary, to track the large amounts of data and calculations needed to generate the schedule durations and resource loadings.

Scope

This analytical study was limited to the specific construction projects required to support two specific lunar base scenarios: the scenario developed for the NASA Office of Exploration's LECS and the scenario referred to as Reference Mission A (referred to as Option 1 in the Planetary Surface Systems Study Period Summary) in the report of the 90-Day Study by NASA in response to the President's 20 July 1989 request for program alternatives. Within each scenario, only those projects involving items of infrastructure having sufficiently defined conceptual designs were analyzed. General criteria for selecting the projects were the availability of (1) design descriptions for the involved hardware, (2) rough order-of-magnitude estimates of the masses and physical size of the pieces to be handled, and (3) descriptions of acceptable site conditions.

Mode of Technology Transfer

Information in this report is appropriate for inclusion in packages of background material for participants in workshops sponsored jointly by NASA and USACE. The techniques used in this analysis will also be useful in preparing mission support documentation after the NASA Space Exploration Institute (SEI) mission is defined.

2 ANALYSIS METHODOLOGY

The methodology used to quantify the operational requirements for lunar construction is based on the premise that the construction projects of interest can be built from a set of elemental construction tasks. A similar approach is being adopted for planning extravehicular activity (EVA) work periods for the Space Station Freedom (SSF), and is being investigated as the basis for an integrated construction project data model[1]. Based on a review of the proposed lunar program objectives and the results of working sessions held during the 1989 Workshop on Extraterrestrial Mining and Construction,[2] the authors determined that 25 basic tasks (21 primary tasks and four secondary, or overhead, tasks) were sufficient to characterize lunar surface construction activities. The overhead tasks were not specifically included in the detailed project analyses because the amount of productive work assumed per day (6 hours out of every 8 hours) took into account an overhead factor (1.25) that included all of the secondary tasks. A set of resources intended to be available to perform these tasks was compiled with the help of the conceptual equipment design team from Pacer Works, Ltd. These tasks and resources (see Table 1) are the fundamental entities used in the operations analysis. For the 90-Day Study, a similar evaluation was performed. However, the 90-Day Study evaluation was more top-level due to time constraints and the concurrent conceptual development of new equipment and facility designs. (Descriptions of the primary tasks defined for this analysis can be found in Appendix A.)

Table 1

Basic Construction Tasks and Resources

TASKS

Transport Pallets		Set Anchors	Survey
Transport Bulk Cargo		Elevate Bulk Cargo	Excavate
Remove Small Boulders	(≤ 1 t)	Connect/Disconnect	Trench
Break Up Large Boulders	(≤ 1 t)	Activate/Test	Grade
Emplace Large Items	(1 t < m ≤ 20 t)	Repair/Startup	Backfill
Emplace Medium Items	(.1 t ≤ m ≤ 1 t)	Transport Crew	Offload
Emplace Small Items	(< .1 t)	Restation Machines	Inspect
Hardware Ingress		Configure Machines	
Emplace Utilities		Set Up/Tear Down	

RESOURCES (Code Letter)

EVA Crew	(A)	Grader Blade	(K)
IVA Crew	(B)	Supervisory Model	(L)
Cargo Bin	(C)	Servicing Module	(M)
Mobile Work Platforms	(D)	Belt Conveyor	(N)
Casters	(E)	Energy Storage Unit	(O)
Crane Assembly	(F)	Unpressurized Rover	(P)
Reverse Clam Shell	(G)	Mining Equipment	(Q)
Robotic Arm	(H)	Payload Unloader w/attachments	(R)
Drill Implement	(I)	Pyrotechnics	(S)
Regolith Bagger	(J)	Hand Tools	(T)

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[1] Francois Grobler, "Symbolic Unified Project Representation (SUPR) Model," *Computing in Civil Engineering—ASCE Proceedings of the Sixth Conference*, (American Society of Civil Engineers [ASCE], 1989).

[2] Bridget M. Register, ed., *Proceedings of the FY89 Workshop on Extraterrestrial Mining and Construction*, Golden, CO, 2-4 May 1989, Lockheed Engineering and Sciences Co. (LESC) Report 27585 (March 1990).

The total mass of the construction equipment for LECS was limited to approximately 6 metric tons. The LECS equipment set consists of two mobile work platforms (MWPs), two transport vehicles, and several attachable implements that can be configured to perform the complete range of work functions needed at the base. Figure 1 illustrates an MWP configured for excavation. These resources can be joined in various combinations to accomplish a broad set of generalized construction tasks. The construction equipment is assumed to be predominantly controlled by teleoperators on the lunar surface. Continuous operations like trenching or leveling are assumed to be controlled remotely from the lander or habitat with occasional EVA required for initial setup and inspection. More precise, complicated, and difficult maneuvers or noncontinuous activities are assumed to require an EVA crew at the site for the entire duration of the task. Operations in the latter category include unloading, loading, and assembly tasks in which high-precision alignments and condition assessments are needed for the entire operation.

The construction equipment for the 90-Day Study was limited to approximately 12 metric tons. The centerpiece of the equipment is one large, highly capable "supercrane," or payload unloader. The payload unloader is essentially a gantry crane with three independently controlled struts, each with powered wheels and two degrees of freedom—rotation around the primary attachment to the main body and telescoping of the struts. This flexible machine will control the payload with six degrees of freedom. Other attachments include a robotic arm, cargo bin, drill, reverse clamshell digger, and leveling blade. The equipment sets designed for both LEGS and the 90-Day Study were designed to meet the minimum performance standards for their respective missions while conforming to mass limitations imposed by the program manifests. More details on both equipment sets can be found in a report to USACE by Pacer Works, Ltd.[3]

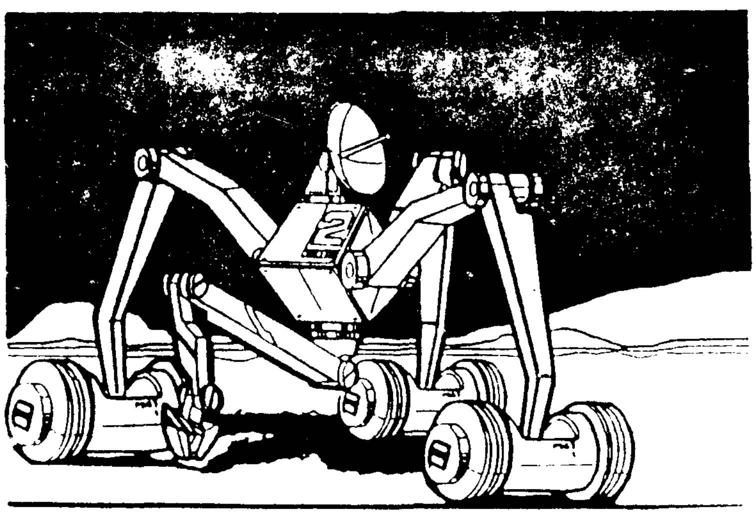

Figure 1. Mobile work platform configured for excavation. (Illustration courtesy of Pacer Works, Ltd.)

[3] James W. Brazell, *Construction Equipment for Lunar Surface Operations*, Draft Technical Report (U.S. Army Construction Engineering Research Laboratory [USACERL], 1990).

The information needed to link the elemental tasks to the appropriate construction resources is shown in Tables 2 and 3. A group of resources is assigned to each task based on the functional capabilities of the equipment and crew. The excavation task, for example, is accomplished by a crew member (Resource B), who teleoperatively manipulates a system that is composed of a reverse clamshell digging implement (Resource G), a mobile work platform (Resource D), an energy storage unit (Resource O), and a supervisory module (Resource L). The assignment of intravehicular (IVA) crew to any of the tasks indicates that an IVA crew member would be directly involved as a teleoperator or remote task controller. The use of an IVA crewmember to monitor every EVA task is an operational requirement that is not included in the standard resource map. This operational procedure is accounted for during the scheduling portion of analysis through the assignment of overhead IVA resources for each task requiring EVA crew.

The productivities indicated in Tables 2 and 3 reflect the estimated performance of the equipment involved and are designed to establish a set of benchmarks for this study. These productivities were estimated based upon terrestrial experience and close collaboration with the construction equipment designer, Pacer Works, Ltd., and USACERL. The productivities of lunar equipment may appear low compared to terrestrial analogues. However, when one considers that the primary pieces of lunar construction equipment have masses of approximately 2 metric tons (approximately 750 lb of gravitational force on the moon) and that their power source is approximately 5 kW, it can be seen that the numbers are appropriate. Typical earthmoving equipment ranges in mass from 30 to 60 metric tons and consumes from 100 to 300 kW of power. The productivity of digging or leveling operations on the lunar surface is further hindered by the very hard and compacted regolith (rocky debris) that is usually encountered 10 to 15 cm below the surface. Furthermore, the mobility and dexterity of the EVA crew are adversely affected by a cumbersome suit and gloves, which will decrease manual productivities.

Note the columns in Tables 2 and 3 entitled "Unit of Work." This category identifies the parameter deemed to be the primary driver in determining the length of time a resource, or set of resources, will be assigned to a task. The identification of work units is an extremely important step in the characterization of the elemental construction tasks. These units of work are used to quantify the productivities of the resources in performing the task, and can be used to indicate the level of effort required for the specific construction projects being studied.

After the elemental construction tasks and resources have been identified and characterized, they must be related to the specific scenario or mission program under study to keep them in the correct perspective. The surface system architecture team and the conceptual designers of various surface elements assisted in identifying a set of construction projects that address the program objectives of the lunar outposts considered here. Each project was then described as a sequence of elemental construction tasks, with quantities of work calculated for each task and maintained in automated spreadsheets (see Appendix B). The hierarchical approach to construction operations definition used in the present study is depicted in Figure 2.

The units of time used to express task duration are man-hours and machine-hours. To determine the project duration in terms of mission-days,* the resources required for each project must be scheduled within the constraints imposed by human and machine performance, operational procedures, and the mission manifest. The constraints on each resource can be assimilated into a composite constraint that will be referred to as *availability*. The availability of each resource varies as a function of time, primarily because the mission manifest dictates the delivery of the construction resources.

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* The term "day" refers to a 24 hour period of time, not one complete lunar day/night cycle. The term day is used as a convenience to allow time to be considered in a manner analogous to construction planning on Earth.

Table 2

Productivity and Resource Assignments for Elemental Construction Tasks
(FY89 Lunar Evolution Case Study)

Elemental Task Name	Unit of Work	Productivity*	Resources**
Survey	points	12 points/hr	AMO
Excavate	volume (m^3)	3 m^3/hr	BDGLO
Remove Boulders	pieces	4 pieces/hr	BCDEH
Break Up Large Boulders	pieces	0.25 pieces/hr	ADIMO
Transport Bulk Cargo	volume (m3) distance (km)	2 m^3 @ 4 km/hr	BCELO
Trench	volume (m^3)	3 m^3/hr	BDGLO
Grade	volume (m^3)	3 m^3/hr	BDKLO
Backfill	volume (m^3)	6 m^3/hr	BDGLO
Offload Pallets	pallets	0.2 pallets/hr	ABDFLO
Transport Pallets	distance (km)	1 km/hr	BCELO
Emplace Large Pieces	pieces	0.2 pcs/hr	ABDFLO
Emplace Medium Pieces	pieces	2 pcs/hr	ADHLO
Emplace Small Pieces	pieces	4 pcs/hr	AM
Hardware Ingress	volume	1.33 m^3/hr	AB
Emplace Utilities	length (m)	500 m/hr	BDHLO
Inspect	points	4 pts/hr	AM
Set Anchors	points	1 pt/hr	BDILO
Elevate Bulk Cargo	volume (m^3)	3 m^3/hr	BDGNLO or BDJLO
Connect/Disconnect	points	4 pts/hr	AM
Activate/Test	systems	4 systems/hr	AM or BM
Repair/Startup	systems	0.5 systems/hr	AM
Transport Crew	distance (km)	10 km/hr	DEO or PO
Restation Machines	distance (km)	4 km/hr	DELO or CELO
Configure Machines	functions	1 function/hr	AM
Set Up/Tear Down	systems	2 systems/hr	AM

* For tasks requiring EVA crew as a resource, the productivity is based on the amount of work that can be accomplished by a two-person EVA crew on average.

** See Table 1 for explanation of resource code.

Table 3

Productivity and Resource Assignments for Elemental Construction Tasks (90-Day Study, Option 5)

Elemental Task Name	Unit of Work	Productivity*	Resources**
Survey	points	12 points/hr	ABP
Excavate	volume (m^3)	3 m^3/hr	BR
Set Explosive Charges	pieces	1 pieces/hr	ABR
Transport Bulk Cargo	volume (m^3) distance (km)	2 m^3 @ 4 km/hr	BR
Trench	volume (m^3)	3 m^3/hr	BR
Grade	volume (m^3)	3 m^3/hr	BR
Backfill	volume (m^3)	6 m^3/hr	BR
Offload Pallets	pallets	0.33 pallets/hr	ABR
Transport Pallets	distance (km)	1 km/hr	BR
Emplace Large Pieces	pieces	0.33 pcs/hr	ABR
Emplace Medium Pieces	pieces	2 pcs/hr	ABR
Emplace Small Pieces	pieces	4 pcs/hr	ABR
Hardware Ingress	volume	1.33 m^3/hr	AB
Emplace Utilities	length (m)	500 m/hr	BR
Inspect	points	4 pts/hr	AB
Set Anchors	points	1 pt/hr	ABR
Elevate Bulk Cargo	volume (m^3)	3 m^3/hr	BR
Connect/Disconnect	points	4 pts/hr	AB
Activate/Test	systems	4 systems/hr	AB
Repair/Startup	systems	0.5 systems/hr	AB
Transport Crew	distance (km)	10 km/hr	ABP
Restation Machines	distance (km)	4 km/hr	BR
Configure Machines	functions	1 function/hr	BR
Set Up/Tear Down	systems	2 systems/hr	BR

* For tasks requiring EVA crew as a resource, the productivity is based on the amount of work that can be accomplished by a two-person EVA crew on average.

** See Table 1 for explanation of resource codes.

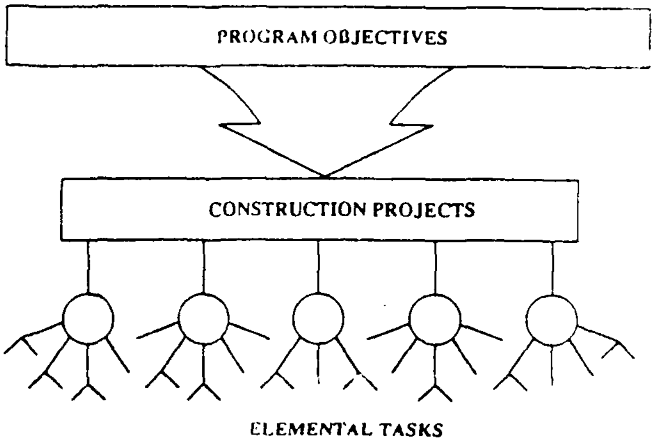

Figure 2. Hierarchical approach to construction operations definition.

Availability can be expressed in different units, depending on the type of analysis being performed. For example, consider a trenching task that requires 45 machine-hours. The machine assigned to the trenching task in the 90-Day Study is the payload unloader with the digging implement attached. Because of energy storage limitations, the payload unloader is constrained to approximately 9 hours (60 kW-hr at an average power consumption of 7 kW) of trenching per 24-hour day. To determine the number of days needed to complete the trenching task, the availability of the payload unloader would be expressed in hours per day. Based on the example task duration in hours, the machine would have to work at the task for 5 days.

Another way of expressing the resource availability is in terms of hours per year. This unit is important because it takes additional constraints into account, such as the constraint that the payload unloader will be scheduled for construction activity only during the 14-day daylight portion of the 28-day lunar day/night cycle. The specification of availability for a time period longer than one day also takes into account the decision to schedule only 80 percent of a resource's time to the nominal construction plan as an initial effort to accommodate a margin for contingency operations. As an example, these factors can be combined with the basic daily availability of the payload unloader to arrive at an annual availability of 1248 hours. This expression of availability is important when performing a feasibility assessment on a specific resource because the total work load for the resource as a function of year can be compared to the availability of the resource as a function of year. If the payload unloader in the present example were assigned to a total of 1150 hours in a specific year, and if the payload unloader had been delivered to the lunar surface, then it would be considered feasible for the payload unloader to complete its assigned tasks given the operational assumptions made in the study. Table 9 and the Gantt charts depicted in this report, however, are based upon the crew and equipment working during both the lunar day and night.

Additional parameters used in the analysis are shown in Table 4 to help the reader understand the level of detail attained in the analysis.

Table 4

Additional Parameters Used in Construction Operations Study

Average Slope at Site (EEI, 1988)	4.7 degrees over 25 m
Allowable Average Slope	2.5 degrees over 25 m
Vol. of Regolith per Area to be Leveled	.15 m3/m2 (.05 m^3/m2 for roads)
Angle of Repose for Disturbed Lunar Regolith	36 degrees
Angle of Excavated Wall Face (from vertical)	30 degrees
Avg # of Systems to be Tested per Machine	4
Average Mass of Package to be Ingressed	100 kg
Traverse Distance from Temporary Landing Pad to Habitation Zone (HZ)	300 m
Traverse Distance from Permanent Landing Zone (PLZ) to (HZ)	5 km
Traverse Distance from PLZ to ISRU Zone	4 km
Width of Area Cleared for Roadways	10 m
Fraction of Systems Requiring Some Troubleshooting Activity	25 %
Average Duration of Troubleshooting Activity	2 hrs
Machine Duty Cycle, Daily	8 hrs per day
Machine Duty Cycle, Weekly	6 days per week
Machine Duty Cycle, Lunar Cycle	entire 4 weeks of cycle
IVA Crew Duty Cycle, Daily	8 productive hrs per day
IVA Crew Duty Cycle, Weekly	6 days per week
EVA Crew Duty Cycle, Daily	6 productive hrs per day
EVA Crew Duty Cycle, Weekly	6 days per week
Airlock Capacity for Equipment Ingress	8 m^3 per ingress cycle
Average Density of Equipment to be Ingressed	0.18 t/m^3

3 LUNAR EVOLUTION CASE STUDY (LECS)

Initial Suite of Lunar Surface Infrastructure

This construction operations case study is characterized by the assumption that no Earth-controlled telerobotic operations will be used to accomplish any of the construction tasks. The initial construction phase begins therefore, with the arrival of a crew on the lunar surface in February 2004. The work to be accomplished during this first manned mission is depicted in the top-level activity network shown in Figure 3. Built up from primitives, the activities in the figure represent over 100 individual construction tasks that are required to characterize this one construction project. The tasks representing the box "Habitat" in Figure 3 are presented and shown in Table 5. Sequences of tasks for the remaining activities are provided in Appendix C.

Estimates of the work content (see Table 5) are based upon simplifying assumptions, conceptual facility designs, the lunar base architecture, and flight manifests. For example, it is assumed that laying out the habitat area is similar in complexity to laying out a house for construction on the Earth, and that the initial habitat is totally self-contained and in one package. It is also assumed that foundation requirements consist of only a level and smooth area with a few screw-type anchors required. As of this writing, the amount of regolith required to cover and shield the initial habitat from radiation is undetermined. Therefore, covering of the habitat is not included in the operations plan. Should regolith shielding be required (without the use of bagging or regolith-containment structures) before the habitat becomes habitable, the time required to complete the habitat would be increased by approximately 20 weeks.

Surface preparation of the habitat area consists of leveling and removing rocks. It is assumed that only minor compaction is required and will be provided by each pass of the construction equipment during normal leveling operations. Boulder removal is assumed to be required and is divided into two categories. Smaller boulders (less than 1 metric ton) will be picked up and moved by the mobile equipment platform with robotic arm or crane boom attachment; larger (over 1 metric ton), unavoidable boulders will be drilled, blasted, or mechanically broken, and removed as smaller pieces. Boulder distribution, based on conversations with NASA scientists, is assumed to be one small boulder per 10 m^3 and one large boulder per 100 m^3 of regolith moved.

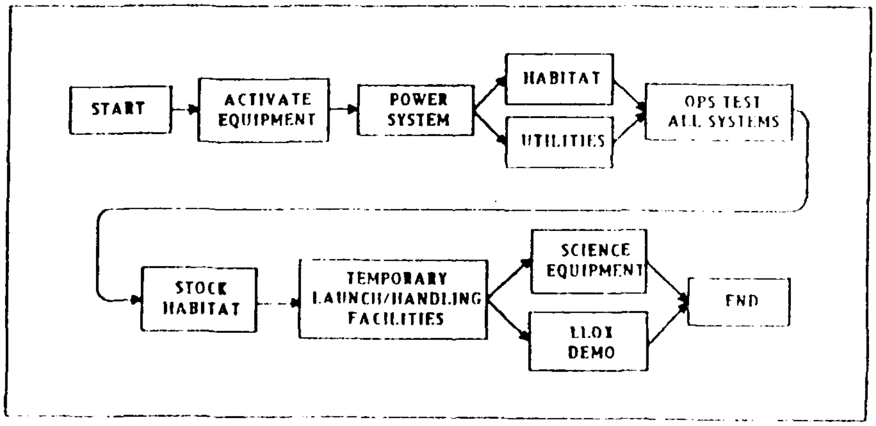

Figure 3. Top-level activity network for first construction sequence.

Table 5

Task Representation for Habitat Construction

Task	Quantity of Work (qow)	Rate (qow/hr)	Duration
Layout Hab Module	12 points	12	1 hours
Surface Prep Hab Module	200 sq meters		3 days
Level Hab Area	30 cu meters	3	10 hours
Remove Small Rocks	3 small rocks	4	1 hours
Remove Large Rocks	3 large rocks	0.25	1 hours
Offload Hab Module	1 lg item	0.2	5 hours
Transport Hab Module	300 meters	1000	1 hours
Emplace Hab Module	1 lg item	0.2	10 hours
Anchor Hab Module	4 points	1	4 hours
Offload Airlock and TCS	2 lg items	0.2	10 hours
Transport Airlock and TCS	300 meters	1000	1 hours
Emplace Thermal Control Radiator	1 lg item	0.2	5 hours
Anchor Thermal Control Radiator	4 points	1	4 hours
Emplace Airlock	1 lg item	0.2	5 hours
Connect Airlock	8 points	4	2 hours
Anchor Airlock	4 points	1	4 hours
Emplace Tent	4 med item	2	2 hours
Anchor Tent	4 points	1	4 hours
Inspect Hab	12 points	4	3 hours
Test Hab Systems	12 systems	4	3 hours
Final Prep/Cleanup	250 sq meters	250	1 hours

The number of connections, whether electrical, fluid, or structural in nature, is assumed to be kept to a minimum. Connection procedures are assumed to be common, simple, and easily performed by the crew with simple hand tools. For example, the connection of the airlock to the habitat was estimated to require eight connection points and 2 hours of work (see Table 5). The balance of the construction projects for the first 7 years of lunar base development were analyzed in a similar manner. Schedule results for the first construction phase, along with resource usage rates for the balance of the projects, are discussed below.

The schedule for the initial construction project is presented in Figure 4. (For a more detailed schedule of activities for this project, see Figure C1 in Appendix C.) As the schedule indicates, the entire group of activities contemplated for the first mission cannot be completed in the 30-day stay that was designated by the LECS as the nominal duration of the first manned visit. Based on the parameters used in this study, a surface stay of more than 100 days is needed to achieve the stated mission objectives. There is, however, the possibility of completing the habitat, power, and utility installation tasks in 30 days. Doing so would allow the crew to move into the habitat and, thus, extend its stay to complete the work.

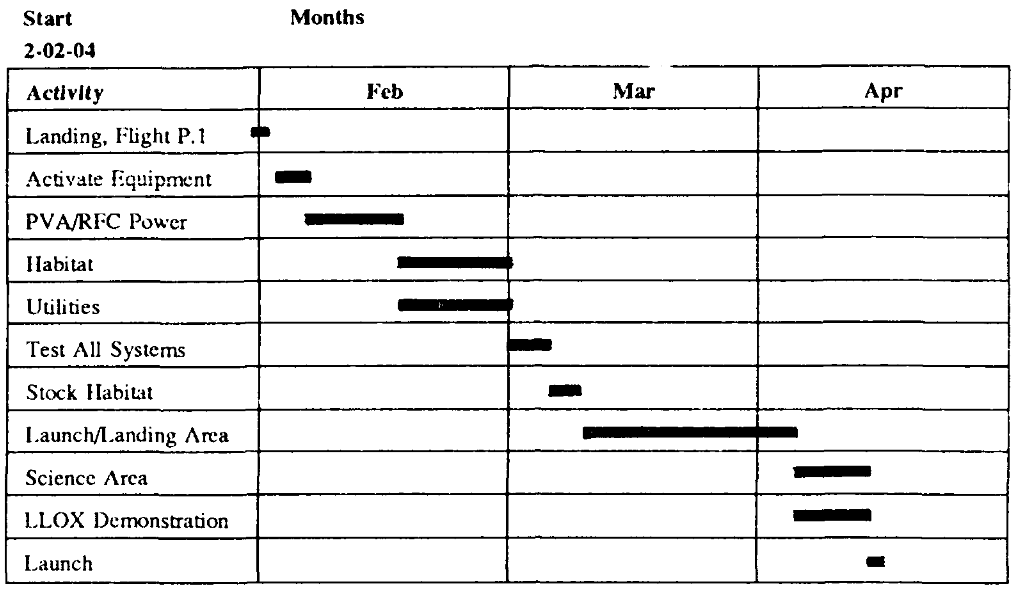

Figure 4. Activity schedule for initial LECS construction project.

Roadways and Landing Pads

Leveling and clearing of roadways and landing pads will require grading, cut-and-fill, surface stabilization, and rock removal operations. The method of surface stabilization is as yet undetermined. It has been assumed that only minor compaction is required and would be provided by each pass of the construction equipment during normal grading operations.

It is assumed that cut-and-fill operations will be kept to a minimum by careful site selection and avoidance of large craters and boulders when possible. It is also assumed that smaller boulders can be readily picked up and moved by the mobile equipment platform with robotic arm attachment. As previously stated, larger boulders are assumed to be drilled, broken, and removed as smaller pieces.

The average slope in the mare regions over 25 meters is 4.7 degrees.[4] Figure 5 illustrates the geometry and calculation for determining the average quantity of regolith movd for leveling purposes. The quantity of cut material, calculated on the basis of the geometry in Figure 5, is 0.26 m^3 per square meter of area to level. This quantity is reduced to 0.05 m^3/m^2 for roadways and 0.15 m^3/m^2 for facility areas to reflect some allowable variations from level and swell of the soil.

Utility Distribution Paths

Several options for utility installation can be considered for extraterrestrial base construction. The utilities can be installed in conduits, bare, on the surface, buried, or elevated. Conduits may ofter more protection but will cost more in launch mass. Bare burial would offer protection from micrometeorites and other hazards but would make access for repairs or modifications more difficult. Either surface- or elevated utility ways would provide ease of access but would expose utilities to other hazards and high

[4] Eagle Engineering, Inc., "Lunar Base Launch and Landing Facility Conceptual Design," *Lunar Surface Systems Studies*, Report 194 NAS9-17878 (NASA Advanced Programs Office, 1988).

temperatures during lunar daylight. Bare burial has been assumed for this case study. It is important to note that all present and future utilities should be considered for initial burial so additional trenching or disturbance of existing utility ways can be avoided. An accurate map of the utility routings—as-built drawings—must be generated as the utilities are installed to allow precise location of utilities for future repair and to avoid damage when excavating in nearby areas.

Advanced Habitation Provision

The inflatable habitat can be delivered in separate parts to facilitate its transport from Earth. Manifest decisions regarding the timing and packaging of these components will have a large impact on the construction project's duration. In LECS the initial configuration would be delivered in three flights over an 18-month period. A 32-week period is needed to prepare the site for emplacement of the structure, so the project start date is November 2005. The emplacement, backfill, and cover operations take an additional 29 weeks once the first part of the structure is delivered in July 2006. The installation of the full complement of thermal control system (TCS) equipment begins in January 2007 and requires 2 weeks to complete. A third flight delivers the life-support equipment for the inflatable in July 2007. The installation of the life-support equipment and a total system test is then performed over a 3-week period. The inflatable can accommodate crew as early as August 2007, but the 5-month period prior to the arrival of additional crew can be used as a trial period for monitoring and validation of critical system performance. An additional installment of laboratory equipment arrives 3 years later, and the setup is estimated to take approximately 2 weeks. Extensive laboratory work could then begin in August 2011. Figure 6 indicates the progression of tasks during the course of the construction project.

Power System Provision

PVA/RFC System

The installation of a photovoltaic array (PVA) and regenerative fuel cell (RFC) is a critical construction activity during the first manned visit to the lunar surface (February 2004 to March 2004). Prior to the layout of the solar array panels, an area must be cleared using the grader configuration of the mobile work platform. No confirmation was received regarding the issue of a standoff (or support)

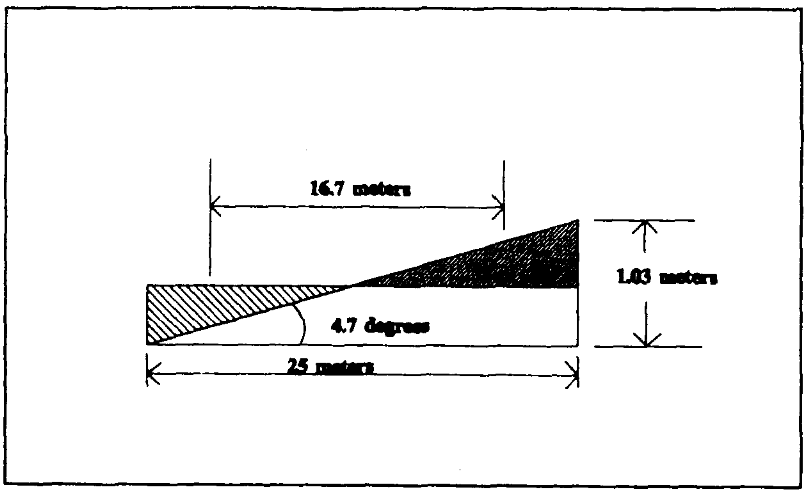

Figure 5. Geometry assumed for calculating grading requirements.

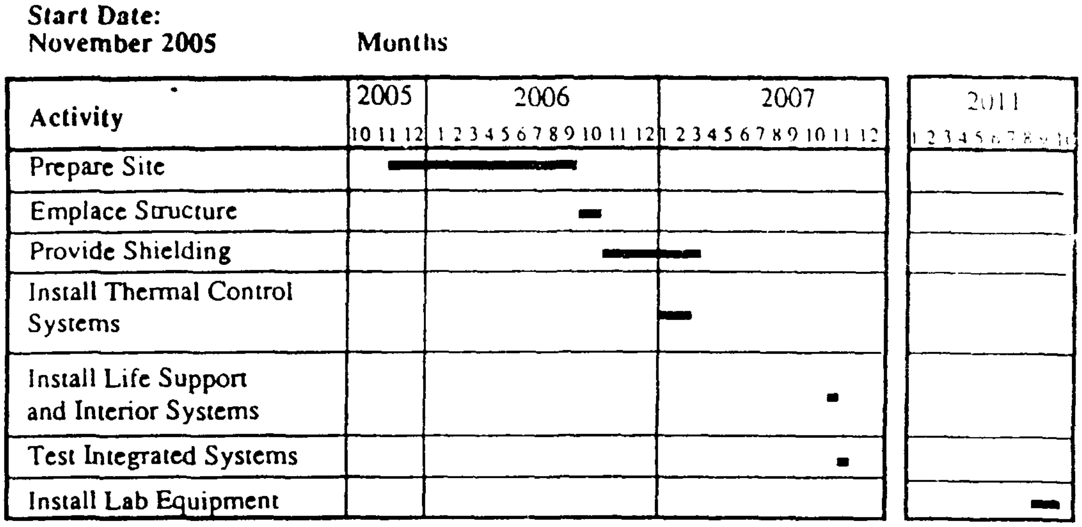

Figure 6. LECS Activity schedule for advanced habitation provision.

structure for the PVA during the FY89 study. The time allocated for the placement of the array assumes that a two-person EVA crew, together with the MWP set up and level the area, then unroll flexible panels on the prepared lunar surface. An alternative design would be to have a standoff structure, possibly integrated with the photovoltaic material, in rigid panels. The difference in setup time between these two methods of installation has not been determined; a more detailed description of the hardware is needed before such a determination can be made.

The tasks listed in Table 6 will be repeated for the installation of an additional PVA/RFC unit in the second manned activity period (July 2004 to January 2005). In 2005, additional PVA hardware is delivered that will be added to the existing array field. The time required to complete the installation of the additional panels is approximately 11 days. This duration is based on the analysis performed for the initial PVA/RFC construction task, together with a scaling factor that accounts for the additional connections and emplacement procedures associated with the larger installation.

SP-100 Class Nuclear Power Systems

The fourth and fifth phases of power system evolution make use of an SP-100 reactor to generate thermal energy. The landing of a self-contained unit that uses thermionic conversion to produce 100 kW of electricity occurs in February 2006. Before the emplacement of this power element, a minimal amount of surface preparation must be scheduled. The basic construction tasks of surveying, trenching, and grading are completed before the delivery of the surface element. The time estimated for site survey and grading (12 hr) is based on the number of points to be marked and the surface area to be cleared before element placement. A separation distance of 1 km was assumed to be the minimum safe distance between the nuclear plant and the habitation zone. This assumption resulted in the estimation of 16 hr of teleoperated machine activity for the construction of a trench 50 m long to carry the lines clear of the immediate plant site, and a trench section 350 m long that will provide protection from the transmission line in the high-traffic areas in the habitat zone. The remaining 600 m of cable will be laid on the surface with markers to indicate the presence of a high voltage power line. There may be some advantages to providing additional insulation by covering the entire length of power cable with lunar regolith, namely improved transmission efficiency and extended material life. The magnitude of these benefits, however, may not warrant the additional trench and backfill operations associated with complete cable burial.

Table 6

Tasks for the PVA/RFC System Installation

Task Descriptions	Duration (hours)
Survey/Layout	2
Surface Preparation	12
Unload PVA/RFC	5
Transport PVA/RFC	1
Emplace PVA	2
Emplace RFC	5
Anchor PVA	2
Connect PVA	2
Anchor RFC	4
Connect PVA/RFC	1
Inspect	2
Test	1
Repair/Start Up	1
Final Prep/Clean Up	1

Once the reactor has been delivered to the lunar surface, it must be offloaded, transported to the designated site, and positioned. Utility connections must then be made and a thorough system inspection performed. No assembly tasks other than utility connections have been assumed since the plant is designed to be a self-contained, preassembled unit. The trenches containing the power cable will be backfilled and any remaining debris from construction is removed from the site. Because the power plant is scheduled to be delivered on a piloted lander with other cargo, the offloading tasks will involve egress of the crew and unloading of the consumables and resupply materials before moving the power plant element to the construction site.

The pieces for a larger (825 kW) nuclear power plant are planned to be delivered in July 2009. A considerably greater construction effort is required for the installation of this surface element. After surveying the site for the plant, a pit (4.2 m in depth, 2.5 m in radius) must be excavated for the reactor. The reactor element is placed in the pit, and the reactor, bulkhead, Stirling engines, and radiators are assembled and tested. Figure 7 provides a timeline for each task required to install the plant.

Oxygen Production Facilities

The surface elements associated with the development of an oxygen production facility at the lunar base are the liquified lunar oxygen (LLOX) demonstration unit, the LLOX pilot plant, and three LLOX production plants. Because a modular approach to the facility buildup is taken, the LLOX pilot plant and production plant are essentially the same system. The construction tasks needed to install the modular plants are listed in Table 7.

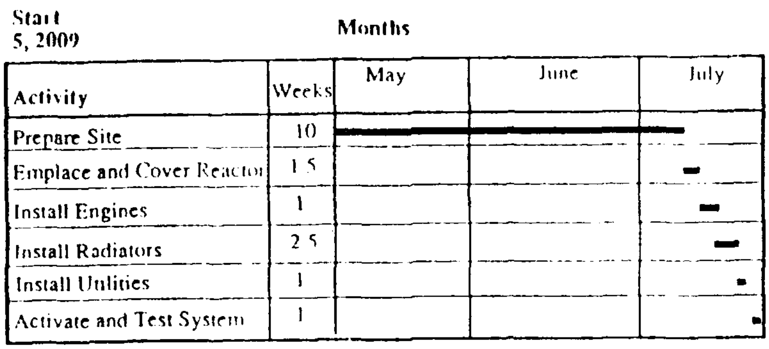

Figure 7. Activity schedule for construction of 825 kW nuclear plant.

Table 7

LLOX Plant Construction Tasks

Task	Task Work Load	EVA Hours	IVA Hours
Select and survey plant and mine sites	36 points	6	3
Prepare utility routings	12 m^3	0	10
Grade area for processing unit	10 m^3	2	2
Prepare pit for LLOX storage tanks	60 m^3	2	20
Set anchors for plant	3 points	2	4
Offload Cargo	7 pallets	2	37
Transport pallets to site	5 km	2	4
Emplace pit scalper	1 large piece	0	5
Emplace process structure	1 large pices	0	5
Emplace external systems	16 med. pieces	0	8
Emplace utilities	200 m	0	2
Connect utilities	12 points	6	3
Test utility connections	12 tests	6	3
Emplace TCS	4 med. pieces	0	2
Connect TCS	12 points	6	3
Emplace storage tanks	3 med. pieces	0	2
Emplace piping	250 m	24	26
Connect piping	24 points	12	6
Cover tanks (backfill & evaluation)	100 m^3	0	30
Activate and test system	400 tests	48	148
Finish/Clean up site	1000 m2 site	12	6

Science Installations

The construction needed for the science missions scheduled for the lunar base is minimal except for the very low frequency (VLF) radio telescope that is to be laid out on the lunar far side in 2013. Table 8 lists the construction projects related to the lunar science installations and the time needed to complete each project.

Summary of LECS Findings

Activity schedules and resource usage estimates have been developed for the first two phases of the LECS, a period of time spanning 8 years. The results are summarized in Table 9. They indicate the feasibility of completing all of the tasks based on the given availability of resources during each project period. While each project involves multiple objectives for infrastructure emplacement, a distinguishing project feature is listed in the table to provide a reference point for subjects that are well documented in the *Exploration Studies Technical Report* (OEXP, 1989).[5] For the first construction project, the availability of construction resources is based on the nominal mission duration of 30 days established by OEXP for the study. All projects after the initial emplacement period were defined to coincide with the semiannual delivery of crew and cargo, and each project goal was established as the completion of all tasks before the delivery of new construction resources and/or material.

Resource usage rates in excess of 100 percent of available resources indicate that a project goal would not be met with the given availability of resources. These usage rates are for construction only and do not include activities such as housekeeping, maintenance, or launch and landing operations. Based on operations-planning documents for Space Station Freedom, base support operations (not including science and *in situ* materials-utilization activities) may account for 25 to 33 percent of the crew's time. Crew activity in excess of 60 percent of the available time indicates periods in the base development where construction project goals need to be reevaluated. This rule of thumb may not be appropriate for the first mission, where greater emphasis may be placed upon construction activities. If an allocation of crew time for science is taken into account, the amount of time that can be dedicated to base construction will be even lower, and the table indicates phases in base development where program priorities must be carefully examined. For example, in the first construction period of 2007, over 70 percent of the crew's available time would have to be devoted to the construction effort in order to meet the goals of the project. The remaining time would be needed for base support operations, leaving little time for manned scientific activity.

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[5] *Exploration Studies Technical Report, FY89 Status, Vol III: Planetary Surface Systems*, Technical Memorandum (NASA Office of Exploration [OEXP], 1989).

Table 8

Construction Activities for LECS Science Installations

Science Installation	Hardware Delivery Date	Project Duration (crew days)	Operational Readiness Date
Geophysical Station #1	2004,2	1	2004,2
Laser Reflectometer	2004,2	1	2004,2
Solar Observatory	2004,2	2	2004,2
Optical Telescope #1	2005,7	4	2005,7
MERI	2005,7	6	2005,8
Biology Lab	2005,7	5	2011,7
Analysis Lab	2005,7	5	2011,7
Earth Observatory	2005,7	4	2005,7
Monitoring Telescope	2005,7	4	2005,8
Infrared Telescope	2006,7	4	2006,7
Ultraviolet Telescope	2006,7	4	2006,8
Optical Telescope #2	2007,7	4	2007,7
Optical Telescope #3	2008,1	4	2008,1
Gamma Ray Telescope	2010,7	4	2010,7
X-Ray Telescope	2011,7	4	2011,7
Plant Lab	2011,7	5	2011,7
Animal Lab	2011,7	5	2011,8
Microbe Lab	2011,7	5	2011,8
Geophysical Station #2	2012,7	2	2012,7
Monitoring Telescope	2012,7	2	2012 7
VLF Telescope*	2013,1	54	2013,9
Geophysical Station #3	2014,1	2	2014,1
Monitoring Telescope	2014,1	2	2014,2
Geophysical Station #4	2015,1	2	2015,1
Monitoring Telescope	2015,1	2	2015,2

* Corrine M. Buoni, *Conceptual Design of a Vehicle to Construct a Lunar Very Low Frequency Array*, Purchase Order (PO) 020011897854, Ref. 000007, (NASA/Johnson Space Center [JSC] Planetary Surface Systems Group, 1989.)

Table 9

Summary of Resource Usage
(Percent of Total Availability)

Project Year, Month	Distinguishing Project Feature	EVA	IVA	MWPs	Trucks
2004,2	Initial Habitat	194	161	110	73
2004,7	Hab Site Prep	47	50	37	12
2005,1	Roadways	60	61	43	16
2005,7	Launch Site Prep	39	40	30	26
2006,1	Inflatable Site Prep	49	51	35	69
2006,7	Inflatable Outfitting	21	22	17	4
2007,1	Roadways	50	51	34	11
2007,7	Shielding Inflatable	64	71	28	55
2008,1	Optical Telescope	5	3	1	3
2008,7	Landing Facility	7	3	5	4
2009,1	MW Nuc. Plant Site	11	12	8	5
2009,7	MW Nuclear Plant	38	20	12	18
2010,1	Resupply	2	2	0	1
2010,7	LLOX Facility	21	13	9	10
2011,1	Resupply	5	4	0	4
2011,7	Lab Installation	15	10	3	7

4 90-DAY STUDY ON HUMAN EXPLORATION OF THE MOON AND MARS

Introduction

A study of lunar and Mars program strategies was performed by OEXP over a 3-month period beginning in August 1989. The primary objective of the study was to produce a set of technically feasible alternatives for carrying out the human exploration initiatives outlined by the President on 20 July 1989. Findings from LECS were used as a guide for the 90-Day Study in defining lunar and Mars base architectures, surface elements, and an operations plan.

Of the technical considerations that were carried over from the FY89 case studies to the 90-Day Study, those related to crew safety were the most critical drivers in the construction operations analysis. Requirements for crew safety dictated that the time needed to install the initial suite of lunar base elements be minimized within the performance constraints of the manned lander and the construction/assembly equipment. For the 90-Day Study, this fundamental guideline was translated into a hard requirement that the first crew be able to move into the initial habitat within 24 hours of landing at the base site. As in the first study, it was assumed that the lunar radiation environment requires that shielding of long-term habitats, i.e., those designed for tours of duty greater than 6 months, be in place before the first long-term occupation. Although the specific amount of required radiation protection depends on a number of factors that have not been completely quantified, the nominal depth of radiation coverage for these habitats was assumed to be 0.5 m.

Although LECS and the 90-Day Study have many common characteristics, there are differences that impact the construction operations requirements. Differences in the 90-Day Study are due primarily to the introduction of new concepts for lunar construction equipment, an increased reliance on teleoperation from Earth during early phases of base development, and the modification of several base elements. The equipment set assumed during LECS was replaced by a payload unloader modeled after a gantry crane with interchangeable implements. This multipurpose vehicle can be teleoperated from Earth or from the base, with on-site supervision by a robot or crewmember. The significance of teleoperation was much more pronounced in the 90-Day Study, a result of the requirement to have the initial habitat ready for occupation within 24 hours of the first crew's arrival on the lunar surface. The use of pyrotechnics to create shaped craters is assumed to be an enabling technique for excavations deeper than 1 m. (At the time of the FY89 case studies, explosives were not considered essential to the excavation tasks and were not included as cargo.) Resized base elements—primarily the habitats and power systems—and modified base development schedules changed the work content of the construction activities being analyzed.

The sections that follow address those aspects of the 90-Day Study that differed from LECS and caused differences in the operational requirements for lunar surface construction. Some construction projects, such as the LLOX plant installation, are essentially the same as those analyzed for LECS. Chapter 3 includes a detailed account of the primary lunar construction projects.

Initial Habitat Installation

The initial habitat installation for the 90-Day Study differs from LECS in both content and execution. The initial habitat in LECS is patterned after the SSF habitat module whereas the initial habitat in the 90-Day Study consists of two similar, but smaller, modules based on the SSF design. The modules—a habitat and laboratory—will be joined to provide two separate pressurized volumes, a feature that satisfies another crew safety requirement stipulated for the 90-Day Study.

The mode of operational control of the construction equipment is also different. In LECS the crew is present on the lunar surface to conduct all construction activities. Constraints were imposed on the

90-Day Study, which required that all construction activities be telerobotically controlled from Earth. The primary constraint is that the crew must move into the habitat within 24 hours after the first manned landing. Two alternatives of accommodating this constraint were considered. One solution would be to leave the habitat on the lander, with self deploying power and thermal control systems so it could serve as temporary living quarters for the first few manned landings. During those landings the crew would construct the second portion of the initial habitable volume—the laboratory module. When the laboratory is constructed, the crew will use it as living quarters while they offload and integrate the first module into the combined habitat/laboratory facility. However, this option was eliminated because of limitations in lander capacity.

The option that was finally adopted achieves the construction of the initial habitat via telerobotic control from Earth before the first crew arrives. The feasibility of constructing the first habitable facility in this manner will require tremendous progress in telerobotics over the next 5 years. For the purposes of the study, it was assumed that sufficient technology and capabilities will exist by 2001 to support the telerobotic construction activities. The production rates of the equipment are decreased by a factor of four as a preliminary estimate of the decrease in productivity anticipated during the periods of Earth-based telerobotic control. The primary reason for the estimated drop in productivity is the round-trip signal delay of approximately 1.5 seconds.

A special aspect of the initial lunar habitat installation in the 90-Day Study scenario is the use of lunar regolith for radiation shielding. The lunar habitat shielding technique for the 90-Day Study (Reference Mission A) requires that a number of bags attached to the habitat be filled with lunar regolith. The machine assigned to this task is the payload unloader with a hopper attachment equipped with a sorting mechanism to reject large pieces of regolith before the material is introduced into the bag. This technique may prove unworkable, however, due to bridging and densification of the regolith that may occur in an operation where the regolith is expected to flow through a funnel-shaped device.

The sequence of steps assumed for filling a bag with one hopper-load of regolith is as follows. First the payload unloader sorts the regolith. Then 2 m^3 of sorted regolith is loaded into the hopper and moved to the habitat. The feed apparatus is then positioned and the regolith is poured into bags. The payload unloader then returns to the pickup site to repeat the task sequence. One cycle of activity is estimated to take 4 hours. Based on the geometry of the habitat and a shield thickness of 1 m, 115 trips were calculated as necessary to fill the shielding bags for a total task duration of about 460 h.

Roadways/Landing Pads

Previous studies indicate that grading, cut-and-fill, surface stabilization, and rock removal operations might be necessary for the preparation of roadways and launch/landing pads.[6] Due to the limited availability of resources in the scenarios under investigation in this study, the issue of site preparation for roadways was revisited. An approach requiring minimal use of resources was adopted for initial roadway preparation with the assumption that additional site development would be pursued during later phases of base activity. This approach was based on the assumption that relatively level sites (as compared to the average slope of the lunar terrain) with low boulder and crater distribution would be selected, and that lunar construction equipment would be designed to be tolerant of somewhat irregular terrain. The degree of irregularity that would actually be acceptable is not yet defined.

For launch and landing pad preparation, it is assumed that cut-and-fill operations will be kept to a minimum due to careful selection of sites and avoidance of large craters and boulders when possible. It is also assumed that smaller boulders can readily be picked up and moved by the mobile work platform

[6] Eagle Engineering.

with robotic arm attachment. Larger boulders are assumed to be drilled, broken, and removed in smaller pieces.

Utility Distribution Paths

In terms of utility distribution, the main difference between the 90-Day Study and the LECS scenario is the slight difference in base layout. The quantities of work were modified to reflect changes in the separation distances between the major activity zones at the base.

Constructible Habitat Installation

In both LECS and the 90-Day Study, the construction of an inflatable habitat is an important milestone in the development of the lunar base. The inflatable habitat was downsized for the 90-Day Study to have a diameter of 11 m, a change that reduced the volume of required excavation from approximately 1400 m^3 to 500 m^3. This reduction in habitat size also resulted in a reduction in the volume of regolith necessary for radiation shielding from approximately 450 m^3 to 240 m^3. In addition, the amount of interior outfitting was reduced to be consistent with the reduction in livable volume, a factor that affects the duration of the outfitting task. The delivery schedule for the inflatable habitat construction project is markedly different from that used in LECS because all pieces for the downsized inflatable habitat are delivered in a single cargo mission (January 2004) instead of the three cargo missions required for the LECS scenario. The use of explosives to facilitate excavation tasks requires site preparation tasks to be initiated in 1999, before sensitive hardware is delivered to the lunar surface. Explosive charges are placed and activated remotely from Earth.

The introduction of unpressurized logistics modules into manifests for the 90-Day Study scenarios did not significantly impact the operations requirements for outfitting the inflatable module because multiple airlock ingress/egress cycles were still required to move supplies into the pressurized inflatable habitat. The transfer of hardware from the logistics module to the habitat will involve depressurization and repressurization of the airlock. The number of airlock pressurization cycles needed to transfer all interior outfitting elements was determined on the basis of element volume. Given the dimensions of the airlock, a nominal capacity can be determined for a single ingress operation. This capacity was calculated to be approximately 11 m^3. With a standard lunar equipment rack (cargo unit) estimated to occupy 1 m^3, 11 such racks can be placed in the airlock per ingress cycle.

Lunar Base Power Systems

There are several construction projects associated with the implementation of the lunar base power system, which evolves over the lifetime of the base to include several different technologies. The major pieces to be installed, and their delivery dates, are listed in Table 10. The first project involves the installation of a PVA/RFC that can supply 25 kW during the lunar day and 12.5 kW during the lunar night. A slight modification was made to the design of the PVA/RFC unit in the 90-Day Study to make it easier to place and deploy using teleoperation. The use of teleoperation for this activity was a direct consequence of the requirement of having the initial habitat ready for the crew to occupy within 24 hours of the initial manned landing. The preparation of a site (2000 m^2) to accommodate the first three PVA/RFC units is estimated to require 125 hours (125 hours by the payload unloader with 50 hours of assistance by the unpressurized rover). These task durations are based on the productivity of the payload unloader when configured for leveling (3 m^3/h) and the productivity of the payload unloader working in tandem with the rover to remove large boulders (2 boulders/h). The installation of a single PVA/RFC unit is estimated to take 13 hours using the payload unloader and rover teleoperated from Earth.

The next power installations are two nuclear reactors, designed to provide 100 kW and 550 kW of continuous power respectively. The site preparation for both plants is initiated by the placement and activation of charges shaped to produce two pits to accommodate the reactors. This task is scheduled for 1999, before the installation of any infrastructure that could be damaged by the blast ejecta. The additional requirements for site preparation are to remove the loosened regolith from the pits (60 hours) and to level a circular area 15 m in diameter at the bottom of the pit for the large reactor site (200 hours).

The installation of the first nuclear power plant is estimated to take 60 hours and the installation of the second one is estimated to take over 220 hours. As in the case of the PVA/RFC unit, the designs for the nuclear power systems were modified in the 90-Day Study to minimize the amount of time needed to get the system online after the hardware is delivered. The radiators for both plants are packaged so each radial segment of the heat rejection system will unfold to its full extension (15 m for the small plant, 25 m for the large plant), as opposed to being delivered in flat panels that have to be connected to form each segment. The primary activities performed after the 100 kW plant is delivered to its prepared site are: (1) radiator deployment, 8 hours, (2) reactor coolant thawing, 24 hours, (3) radiator apron placement, 16 hours, and (4) system activation and test, 10 hours. Although a detailed design of the 550 kW power plant was not available at the time of this study, a new design philosophy was introduced in an effort to reduce the number of separate pieces to be handled during the installation. The new design consolidated many pieces involved in the construction of the 850 kW power plant used in the LECS scenario, and was assumed to result in a 50 percent reduction in installation time.

LLOX Plant Installation

In the 90-Day Study, the development of a LLOX production capability is initiated in 2003 by the delivery of a self-contained demonstration unit that requires no site preparation and minimal assembly. All of the hardware needed to construct an operational LLOX plant capable of producing 60 metric tons per year is delivered in 2010. The layout of the production facility is the same as that described for the LLOX plant used in LECS, but the plant has been resized to meet the production objective with a single unit (as opposed to the four units used in LECS). This reduction in the number of processors is assumed to reduce the construction time of the LLOX facility by a factor of four, based on the operations analysis performed for construction of the LLOX facility in LECS. The justification for this result is that fewer processing plants will need to be assembled and checked.

Table 10

Major Pieces of the Lunar Base Power System and Dates of Delivery (90-Day Study, Option 1)

Element Name (day power/night power, in kw)	Date of Delivery
PVA/RFC (25/12.5)	July, 2000
PVA/RFC (25/12.5)	January, 2001
PVA/RFC (25/12.5)	July, 2001
Nuclear Power Plant (100/100)	January, 2003
Nuclear Power Plant (550/550)	March, 2008

5 ISSUES COMMON TO THE LECS AND 90-DAY STUDY SCENARIOS

A number of issues common to both the LECS and 90-Day Study scenarios provide insight into the general issue of extraterrestrial construction operations and suggest logical points of departure for more specific research.

Robotics Technology Issues

The LECS scenario was based on on-site (EVA or IVA) construction equipment operation and task performance. The 90-Day Study took the alternative approach, which uses telerobotics from Earth to start the site preparation tasks before the arrival of crew. From a comparison of these two approaches a fundamental observation can be made: a plan that makes use of extensive teleoperation from Earth when humans are absent from the site has the advantage of decreasing safety risks to the crew but has the disadvantage of exposing the program to different types of risk. To achieve the same insulation from risk as a plan that does not depend on unattended Earth-based teleoperation, the reliability of the equipment involved must be very high. For an activity that relies on Earth-based teleoperation, the risk associated with a given failure mode is higher than it would be if crew were available on the work site because the opportunities for repairing the failure are diminished.

To meet the deployment dates for lunar construction equipment (2003 for either scenario), final system designs must be completed by the mid-1990s. Considering the current level of automation and robotics employed or being developed by the construction industry, however, dramatic advancements in the area of automated operators for construction equipment in the next 5 to 7 years are considered unlikely. Based on these assumptions it is reasonable to believe that a lunar construction operations plan calling for Earth-based teleoperation before the arrival of crew would require a substantial investment in the area of applied A&R. The technology development program for teleoperable construction equipment should start within the next 2 to 3 years to realize a 2003 deployment date.

On the other hand, an operations plan that relies on crew to perform on-site monitoring, periodic maintenance, and troubleshooting can successfully employ currently existing A&R capabilities.

Radiation Protection Measures

The amount of *in situ* materials needed to provide adequate protection from both galactic cosmic radiation (GCR) and solar particle events is a major driver of construction operations timelines. The requirement for GCR radiation protection has not yet been determined for the lunar or Mars environments, but the value is expected to lie in the range of 50 to 700 g of regolith per square centimeter of surface for habitats intended for tours of duty longer than 6 months. In addition to being especially sensitive to the amount of cover to be provided, the task of providing *in situ* materials protection also depends greatly on the technique used to cover the habitats. Since project durations are especially sensitive to soil-handling requirements, the impact of cover thickness and cover placement technique to total project duration was calculated. Figure 8 shows the comparison between direct regolith cover, direct regolith cover with retaining walls, and contoured cover for a range of radiation protection requirements. The use of a standoff structure in conjunction with these shielding techniques was not included in this analysis, but is an important area for future investigation.

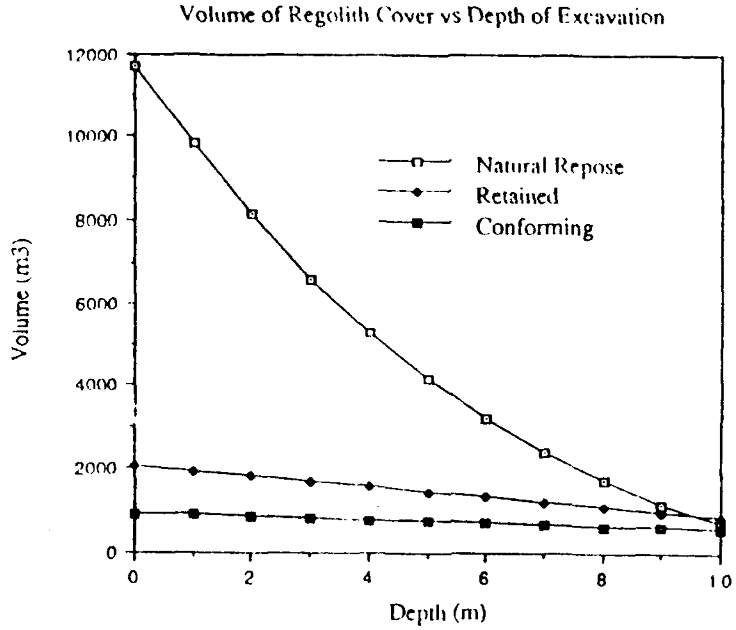

Figure 8. Comparative volumetric analysis of inflatable habitat shielding techniques.

For the shielding techniques mentioned above, the depth of the pit is another important consideration. Figure 9 shows the relationship between the pit depth and the volume of regolith that is handled in the excavation, backfill, and cover tasks. Since the productivity of the digging task can be an order of magnitude lower for the layer of lunar regolith below the top 15 cm of gardened (meteorite-pulverized) regolith, it may be advisable to pursue techniques that do not require digging below 15 cm. Instead, it may be wise to place the habitats on the surface and pile the easily obtained, unconsolidated layer of regolith as a cover.

Interior Outfitting of Pressurized Volumes

An important consideration in planning the timeline for outfitting the inflatable habitat is the packaging of interior system hardware. This is important for estimating the time needed for offloading cargo transport pallets from a lunar lander, disconnecting cargo packages from their pallets, transferring the packages from vacuum to the pressurized volume, and installing the interior systems. Generally, the size of each hardware element will be limited to the dimensions of the airlock used for cargo ingress and to the materials-handling capabilities of the crew. If some hardware elements must be larger than the cargo airlock, it may be useful to consider using a temporary airlock that is larger than the regular one.

Utility Routing and Accessibility

The routing of utilities between surface elements should be planned with long-term base operation in mind. To facilitate the testing and potential replacement of utility segments, it may be desirable to place access stations at various points along the route. High-voltage power transmission lines can also be used to transmit communications signals, especially in systems where few terminals exist to break up

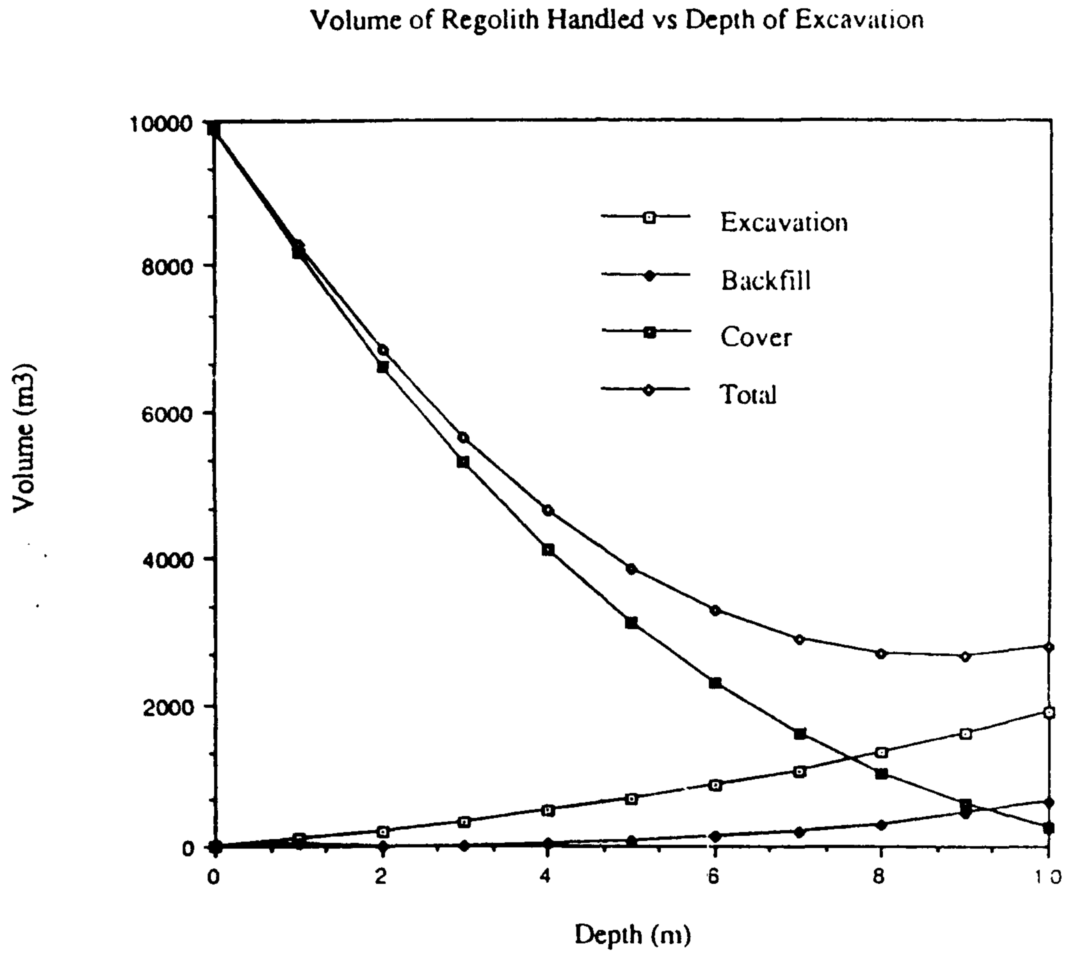

Figure 9. Volume of regolith handled as a function of pit depth, direct burial.

Coordination of Crew and Machines

The most time-consuming construction activities in both the LECS and the 90-Day Study scenarios were those associated with handling regolith. The primary regolith-handling tasks considered in this study were excavation, grading, trenching, and backfilling. The repetition exhibited during the execution of these tasks provides an opportunity for limited automation of some sequences within the activity cycle. According to the information gathered during these studies, it is possible to develop control systems that would allow the crew to direct these activities from a remote site. A large fraction of the excavation, grading, trenching, and transporting of regolith could be carried out by a teleoperator from inside a pressurized work area. Any detailed manipulation of the equipment needed to refine the site prior to placement and assembly could be performed by an EVA crew if necessary. The connection of component pieces and utilities, testing, and troubleshooting during the project are assigned to an EVA crew that may or may not be assisted by an IVA crew member operating a robotic arm. Before the initiation of a new construction project, an EVA crew will survey the site, set up any command, control, and communications equipment required, and configure the machines for the scheduled tasks. Periodically throughout the project, the EVA crew may be called upon to replace an RFC unit or reconfigure a machine.

A typical schedule of activities for a construction project over a 24-hour period during the daylight portion of the lunar cycle is shown in Figure 10. This schedule assumes that the base operates on a single-crew shift and can only allocate a maximum of three crew members to the construction project at

any one time. Also, only four EVA periods are scheduled for construction tasks during a work week. Figure 11 illustrates the additional capability available when the base population grows to eight crew members and a double shift can be accommodated during a 24-hour period. The coordination of EVA shifts with the RFC charge/discharge cycle will be an important consideration when the maximum utilization of construction machinery is required.

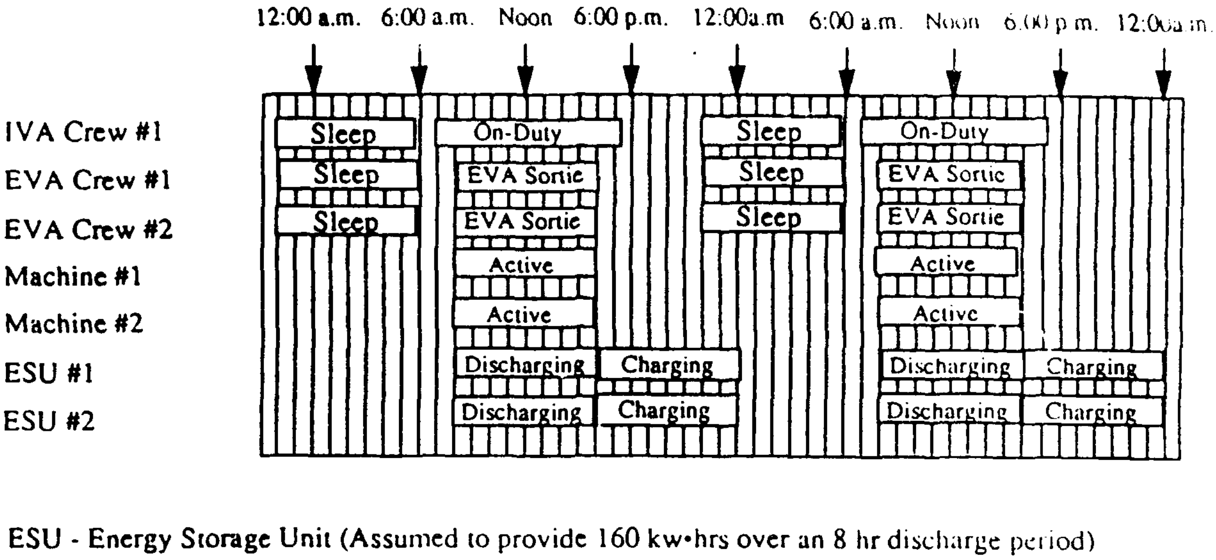

Figure 10. Work schedule for coordination of manpower, machines, and power: single shift operation.

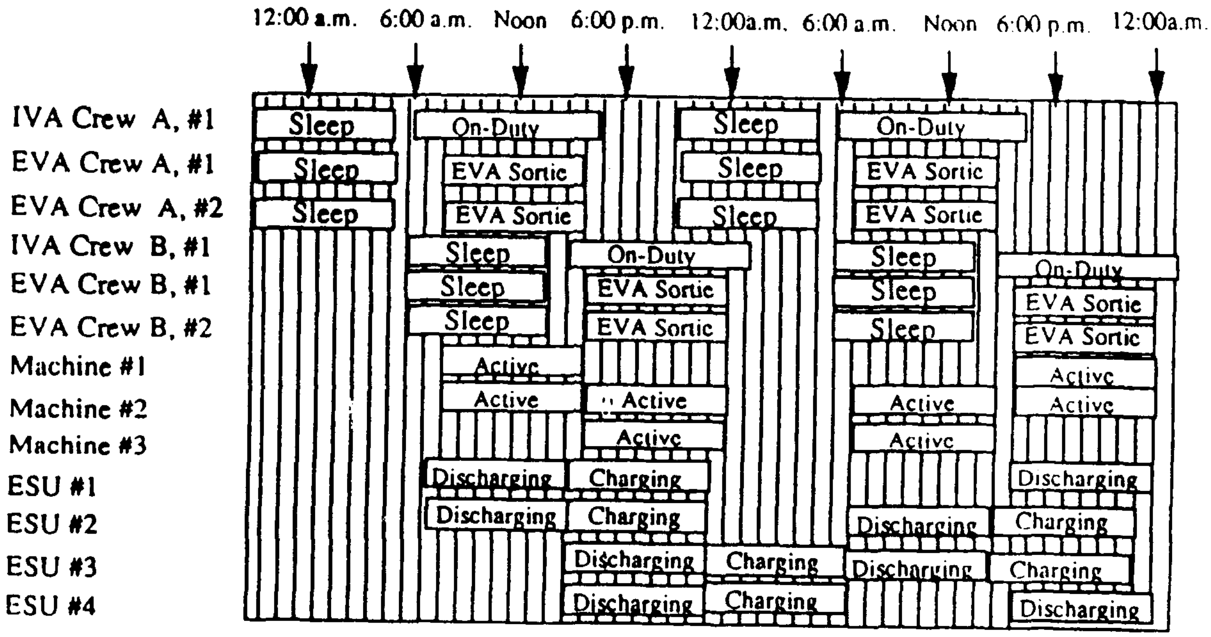

Figure 11. Work schedule for coordination of manpower, machines, and power: double shift operation.

6 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The conclusions that can be drawn from these construction operations analyses fall into the categories of project feasibility, equipment performance, and element design.

Project Feasibility

- The construction operations for all LECS projects beyond the activation scenario are feasible.
- The initial 30-day tour of duty is not long enough to accomplish the objectives of the LECS activation mission.
- The level of A&R required to accomplish the objectives of the 90-Day Study scenario is beyond the capability of currently available technology.

Equipment Performance

- The quantity of work required for road construction can be treated as negligible if the equipment is designed to be tolerant of irregular terrain (e.g., capable of boulder avoidance, slope navigation).
- The two equipment sets used in the operations analysis meet the minimum standards for performance within the mass limitations imposed by the program manifests.

Surface Element Design

- Initial habitats must be designed for constructibility, especially given the strict schedule constraints for the early manned missions.
- The individual pieces of a surface element must be designed for ease of packaging for all segments of the space transportation process.
- Modularity in design is highly desirable from an assembly perspective. Standardized connections and attachment points will increase the productivity associated with assembly and reduce the risks associated with construction operations.

Recommendations for Additional Studies

As previously stated, the results of this analytical study are intended to be a point of departure for future work in the area of extraterrestrial construction operations analysis. Additional studies must be pursued to compare, contrast, and extend the body of knowledge in the field of extraterrestrial

construction, a multidisciplinary field that will continue to grow in importance in the realization of space exploration objectives. The following topics are recommended as necessary areas of further study:

- Base initialization scenarios
- Construction automation and robotics
- Coordination of crews and machines
- Regolith-intensive construction activities
- Base constructibility
- Environment-tolerant construction equipment design
- Construction system reliability
- Construction project risk
- Construction project cost.

A broad study space should be maintained in any such research to give adequate coverage to competing options for construction equipment and techniques during the conceptual design phases of program development. Flexibility is needed to consider changes in manifest content or scheduling constraints during the design process. If a problem is overdefined or subject to too many constraints early in the design process, many favorable alternatives may be overlooked. In addition to broad coverage of alternatives, an unbiased set of selection criteria should be developed for the purposes of effective decisionmaking. These criteria are needed before the decisionmaking process begins.

Base Initialization Scenarios

New and innovative approaches to the problem of constructing the initial suite of lunar base elements —those items needed to provide the first level of capability at the base—should be developed and compared to the approaches currently assumed in the LECS and 90-Day Study scenarios. One principal issue to be addressed by an initialization strategy is the tradeoff between schedule and performance, where the term performance applies to both the level of support afforded by the initial base configuration and the productivity of the construction equipment and crew. An example would be the effect of loosening the requirement to have the initial habitat, just one piece of the initial configuration, ready for the crew to occupy within 24 hours of landing. The degree of automation required to install the initial lunar habitat may be considerably reduced if the time allowed for initial base construction is on the order of 4 to 6 weeks instead of 2 or 3 days. This additional construction time can be provided only at the expense of designing a higher degree of habitability into the lander or by including a piece of removable infrastructure (e.g., a "construction shack") on the lander to serve as living quarters during the initial construction project. Another approach to investigate would be the use of a smaller, preassembled initial base configuration that requires less integration and testing.

It has also been suggested that two smaller habitats, resized so each provides half the volume needed for a 6-month tour of duty, be used to bootstrap the base during the initial construction phase. One of the resized habitats would remain on the lander with self-deployable power and thermal control systems, serving as a temporary shelter for the crew. The crew would live there while installing the second habitat and its support infrastructure on the lunar surface. After the surface habitat is installed, the crew would occupy it as the home base, unload the first habitat from the lander, and integrate it into the home base.

Another alternative may be to shorten the schedule by increasing the number of resources. With relatively small increases in the number of resources it would be possible to significantly shorten the

schedule. For example, two additional crew members and a few more implements would make it possible for two EVA teams to operate simultaneously together or at different sites. This additional capability would be especially helpful during the first construction project, when the demand for EVA (relative to availability) is greatest.

Construction Automation and Robotics

The application of telerobotics—the integration of teleoperation and robotics—to lunar surface construction was assumed in both the LECS and the 90-Day Study scenarios, with the latter requiring Earth-based teleoperation of construction equipment in the earliest phases of base activity. An important issue to be resolved is the degree to which teleoperation versus automation is used for different construction tasks. Another question to be resolved is whether the integration of teleoperation and robotics is accomplished through "traded" or "shared" control. An example of a task that could be performed under traded control is a leveling operation in which the operator teleoperatively positions the machine at the work site and the machine automatically carries out a repetitive sequence of passes. An activity suitable to shared control would be the inspection of an irregular surface, where the operator teleoperates an inspection sensor in a complex pattern over the surface and the automated system keeps the sensor the correct distance above the surface. Increased operator efficiencies are anticipated for tasks performed under shared control because repetitious aspects of the task will be handled automatically.

The feasibility, in accordance with limits on cost and schedule, of achieving the new technologies necessary to realize Earth-based teleoperation of lunar construction equipment should be investigated. In addition to the identification of engineering requirements for teleoperable construction equipment, assessment of the cost associated with the corresponding technology development programs must be assessed.

Coordination of Crew and Machines

Given the cost and risk associated with the design and development of teleoperable construction equipment, it is also important to consider construction system productivity as a whole. System productivity is a measure of the integrated performance of the operator and the equipment, and the division of responsibilities between the two. This topic would address the rate at which the capabilities defined in the studies of construction automation and robotics can be used. In addition, this study should also cover the topic of contingency modes of operation for partially autonomous equipment, i.e., allowing a human operator to intervene during a task.

Regolith-Intensive Construction Activities

Construction tasks that involve the movement of lunar regolith were found to be the most time-consuming activities in the projects defined for the LECS scenario. These tasks include excavation, surface leveling, compaction, stabilization, and foundation installation. A study is needed to assess the sensitivity of these tasks to changes in site conditions. The range of task productivities that correspond to the expected range of lunar site conditions can then be used to calculate the impact of site selection to construction project schedules. Using current knowledge and theories on the distribution of surface and subsurface features, it is possible to calculate the variability in machine productivity for a fixed set of construction equipment. Also, the construction equipment requirements of mass, power, and complexity needed to achieve a fixed set of productivity goals for a range of possible site conditions can be calculated and indirectly translated into cost. This would indicate the cost of designing for the most challenging site, and thereby provide a measure for evaluating the need for precursor missions to determine site conditions

with greater certainty before equipment designs are finalized and the equipment is built. This study would determine how valuable highly accurate information is in construction system design and operation.

At a more detailed level of engineering investigation, a comparative study of surface stabilization techniques (including field and/or laboratory experimentation) is needed to quantify a set of candidate regolith-handling techniques. The results of such a study could then be easily incorporated into a construction operations analysis.

Base Constructibility

Detailed constructibility studies are needed to minimize the work associated with the installation of lunar infrastructure. The studies should address the integrated application of construction knowledge and experience during the planning, design, and field operations of a project. Surface elements and the physical interfaces between elements need to be designed with simplicity and minimum mass in mind. Decisions must be examined throughout the planning and design process in light of the information gleaned from the constructibility perspective. Activities recommended for this constructibility effort include:

- Determining more efficient methods of construction after mobilization of field forces
- Allowing construction personnel to review engineering documents periodically during the design phase
- Assigning construction personnel to the engineering office during design
- Implementing a modularization or preassembly program.

Several issues must be considered to achieve constructibility. The highest priority issues for near-term constructibility studies are the determination of (1) site layouts that promote efficient construction as well as efficient operation and maintenance, (2) module/preassembly designs that facilitate fabrication, transport, and installation, (3) designs that promote accessibility of the facility by personnel, materials, and equipment, and (4) designs that facilitate construction under the harsh environmental conditions on the moon.

Environment-Tolerant Construction System Design

A study is needed to determine the amount of shielding needed to provide adequate protection from both galactic cosmic radiation and solar particle events. Considerable work has already been done to develop models of the effects of various doses of these radiations on the human body and the effects of secondary radiation created by the interaction of incoming radiation and the shielding material itself. The existing data could be used to generate a nominal requirement that follows the standard of ALARA (as low as reasonably achievable) that is used in the nuclear industry to establish safety guidelines for radiation workers. The findings of this study could then be incorporated as part of an extraterrestrial construction standards document that was suggested at the 1990 Workshop on Extraterrestrial Mining and Construction.

The use of a secondary structure that prevents regolith shielding from coming in direct contact with the primary structure was not included in the operations analysis for the LECS or the 90-Day Study scenarios, but such a structure should be examined from a construction operations perspective. The use of standoff structures or retaining walls may prove to be more operationally efficient because of the reduced volume of regolith needed to provide radiation protection. The tradeoff between the amount of work

required versus the additional launch mass of the secondary structure must be studied before a conclusion can be made.

Construction System Reliability

Important characteristics of the construction equipment are the design life and the maintenance requirements, all of which contribute significantly to the life cycle requirements for system resupply. The penalties associated with longer design lifetimes for surface elements must be determined and compared to the benefits of a reduced maintenance burden. In addition, the maintainability of the base as a whole may be substantially improved by adopting an integrated maintenance strategy that requires modules to be stocked as replacement units.

Construction Project Risk

A risk assessment for each lunar base construction project should be performed as an additional consideration during tradeoff studies between various options. In the 90-Day Study, risks were identified and described for space systems, elements, and subsystems. Risk abatement plans were also explored. These qualitative assessments of program risk are the first step toward the development of a strategic plan that takes advantage of favorable events (such as technology breakthroughs, budget increases) and gracefully absorbs unfavorable events (such as schedule delays, launch failures, budget decreases). The next step is to quantify the identified risks to evaluate the relative strengths of candidate technologies and operational strategies.

Construction Project Cost

Cost is another measure that should be considered in evaluating various construction strategies. Parameters that will drive the cost are schedule, equipment maintenance, initial acquisition cost, consumables, and manpower. Using cost estimating relationships that accurately reflect the type of equipment and construction techniques employed for the lunar base program, designers can use cost as one criterion for selecting the most effective construction systems.

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APPENDIX A: TASK DESCRIPTIONS

Typical tasks related to lunar surface construction are described below. Not all of the tasks in Table 2 are included; those not described here are either short-term, minor, or self-explanatory.

Survey

The surveying task is work required to physically lay out and mark the lunar surface to enable the proper placement of facilities and other infrastructure, such as landing pads, roads, and utilities. The resources required to accomplish this task in LECS are a two-person EVA crew, small surveying equipment, and a rover. During the first manned stay, no rover is present.

Excavate

The excavation task is work necessary to extract regolith from the lunar surface for purposes of creating a hole or recess required for a surface infrastructure component or for gathering regolith to use as blast barriers or habitat radiation protection. The excavation device is a mobile work platform with a reverse clamshell digger attachment. Excavation will also require a supervisor module, a full-time IVA controller/monitor, and a part-time (25 percent allocation of its total available work time) EVA crew of two to setup and inspect the work.

Remove Small Boulders

Boulders are expected to be encountered during tasks such as leveling and excavating. Small boulders are defined to be those that are too large to be easily moved by the digging or leveling instrument but small enough for a robotic arm attachment to grapple and remove from the work area. Small boulders are defined as having a mass greater than 0.1 metric ton and less than 1.0 metric ton. The resources required for this task are a two-person EVA crew, one mobile work platform with a robotic arm attachment, a truck, and a rover.

Break Up Large Boulders

Large boulders are defined as exactly 1.0 metric tons or greater. These boulders must be drilled and blasted, or mechanically broken into smaller pieces and removed. A contiguous quantity of rock may also be considered a large boulder. That is, the unit of work is defined as that required to remove 1.0 metric ton of rock, even if that rock is part of a larger contiguous mass. The assigned resources for this task are a two-member EVA crew, a mobile work platform, a drill attachment, a robotic arm attachment, a truck, and a rover.

Transport Bulk Cargo

Bulk cargo is considered to be regolith. The transportation is assumed to be a bin that is moved along the surface by a utility vehicle. For LECS, two 2-wheel dump trucks with a capacity of approximately 2 m^3 perform this task. In the 90-Day Study, a cargo unloader/MWP with a bin attachment performs the task.

Trench

The trenching task is the work necessary to dig trenches for utilities such as thermal control piping and electrical wiring. The resources assigned for this task are one IVA equipment operator, a mobile work platform, a digger attachment, and a part-time (25 percent allocation) two-person EVA crew team with a rover.

Level

The leveling task involves smoothing via cut-and-fill operations to provide a level (or relatively level) surface for the placement of facilities, or for roadways and landing pads. The resources assigned for this task are one IVA equipment operator, a mobile work platform, a leveling attachment, and a part-time (25 percent allocation) two-person EVA crew team with a rover.

Backfill

The backfill task represents the work necessary to place regolith in those areas where excess regolith was removed to emplace a facility or structure (e.g., utilities, habitat). The resources assigned for this task are one IVA crew, a mobile work platform, a leveling attachment, and a part-time (25 percent allocation) two-person EVA crew team with a rover.

Transport Large Items

Transporting large items includes transporting near-full-capacity loads of smaller items. The task is intended to reflect the care that must be taken when the surface transport vehicle is operating near its capacity. This task requires a two-member EVA team and two trucks.

Emplace or Off-Load Large, Medium, and Small Items

It is assumed that the off-loading of items from the lander and emplacing/assembling items are of similar difficulty. Large items are those between 1 and 22 metric tons. They are too large for a robotic arm to handle and must be moved using a crane or jack type of device. Medium items are those items from 0.1 to 1 metric ton and within the handling capability of a robotic arm. Small items are defined as less than 1 metric ton, and are within the capability of the crew to handle with approximately 18 kg gravitational force on the Moon. Resource assignments are a two-person EVA team, two trucks, and two mobile work platforms.

Emplace Cables

This task represents the work required to lay cables such as electrical power cables in a trench or on the lunar surface. The assignments are a two-person EVA team, a rover, and one mobile work platform.

Emplace Pipes

This task represents the work required to install pipes such as thermal control pipes on the surface or in trenches. Resource assignments are a two-member EVA team, two trucks, and a mobile work platform.

Inspect

The inspection task is considered to be primarily visual inspection to ensure the quality of such characteristics as fit, alignment, and the surface condition of critical components. Resource assignments are a two-member EVA team and a rover.

Set Anchors

This task represents the work required to secure to the surface such items as foundations of facilities, anchor cables, and navigation beacons. Resource assignments are a two-member EVA team, a rover, a mobile work platform, and a drill attachment.

Elevate Bulk Cargo

This task primarily represents covering the habitats with regolith. The elevation device is a conveyor. Resource assignments for this task are the conveyor, two trucks, a mobile work platform, one IVA person, a part-time two-person EVA crew team, and a rover.

Connect/Disconnect

The connect/disconnect task is considered to include all connections, whether structural, electrical, or piping. Resource assignments are a two-person EVA team and a rover.

Activate/Test

The activate and test task includes mechanical and power-on tests. The factor of difficulty is the complexity of the test to be performed. The resource assignments are a two-person EVA team, one IVA operator, and a rover.

Repair/Startup

The repair and startup task represents repair work that must be done as a result of the activate and test task. The resource assignments are a two-member EVA team, one IVA op rator, and a rover.

Final Preparation/Cleanup

The final preparation and cleanup task is primarily viewed as the work involved in leveling regolith in an area once the work is done. Since a construction area may be left scarred and rutted by the construction equipment, it is considered necessary to smooth the area for future foot traffic or vehicles. The resource assignments are a part-time two-member EVA team and a rover (25 percent allocation), one IVA operator, and one mobile work platform with leveling attachment.

Ingress Into Habitable Volumes

This task includes moving consumables and hardware into habitable volumes. No logistics module was included in LECS, so all items to be ingressed must be moved by the crew manually through the airlock. Airlock volume and the operation cycle time are considered key factors affecting the productivity of this task. The unit of measure is the volume exchange rate of the airlock combined with the productivity of off-loading small items. The resource assignments are a two-person EVA crew, one IVA operator, and two trucks.

APPENDIX B: QUANTITY-OF-WORK SPREADSHEETS

The following tables describe each of the 6-month construction periods for the FY89 Lunar Evolution Case Study (16 tables to describe construction activities from February 2004 to December 2011) in terms of fundamental tasks. The tables were generated from Lotus/Symphony® spreadsheets that were converted into Microsoft Excel® spreadsheets for clearer presentation. The tasks shown in bold letters are the top-most level of tasks in the hierarchy used to describe the project. Italicized tasks indicate the next level in the hierarchy and the tasks in plain font are the lowest level of detail provided.

Each task in a given construction period is defined by a quantity of work, expressed in units of work such as cubic meters of regolith to be moved in the case of excavation. Task durations are calculated in each spreadsheet based on the productivities of the construction resources and the quantity of work to be performed. The column "duration type" is used to differentiate from a task heading that is used to encapsulate a group of tasks from a lower level task that has an individual quantity of work assigned to it.

Table B1. Quantities of Work for Base Initialization Construction Project (Page 1 of 3)

BASE INITIALIZATION						
February 2004 - June 2004						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	**Activate Equipment**		0			
2	Offload MWPs	1	1	2	med items	2
3	Test MWPs	2	1	8	systems	4
4	Offload Trucks	1	1	2	med items	2
5	Test Trucks	2	1	8	systems	4
6	Offload FCP Cart	5	1	1	lg item	0.2
7	Test FCP Cart	1	1	4	systems	4
8	Offload Implements	3	1	10	sml items	4
9	Offload TC Cart	5	1	1	lg item	0.2
10	Test TC Cart	1	1	4	systems	4
11	Offload Liquifaction Tanks	5	1	1	lg items	0.2
12	Test	1	1	4	systems	4
13	**Install PVA/RFC**		0			
14	Layout PVA/RFC	1	1	12	points	12
15	*PVA/RFC Surfact Preparation*		0			
16	Level PVA/RFC	20	1	60	cubic meters	3
17	Remove Sml Rocks	2	1	6	pieces	4
18	Remove Lg Rocks	2	1	0.6	pieces	0.25
19	Unload PVA-RFC	5	1	1	lg item	0.2
20	Transport PVA/RFC	1	1	300	meters	1000
21	Emplace PVA	2	1	4	med items	2
22	Emplace RFC	5	1	1	lg item	0.2
23	Anchor RFC	4	1	4	points	1
24	Connect PVA	2	1	8	points	4
25	Anchor PVA	4	1	4	points	1
26	Connect PVA/RVC	1	1	2	points	4
27	Inspect PVA/RFC	1	1	4	points	4
28	Test PVA/RFC	1	1	4	systems	4
29	Repair/Startup	2	1	1	systems	0.5
30	Final Prep/Cleanup	1	1	250	square meters	250
31	**Install Habitat**		0			
32	Layout Hab Mod	1	1	12	points	12
33	*Habitat Surface Preparation*		0			
34	Level Habitat Site	10	1	30	cubic meters	3
35	Remove Small Rocks	1	1	3	pieces	4
36	Remove Large Rocks	1	1	0.3	pieces	0.25
37	Offload Habitat	5	1	1	lg items	0.2
38	Transport Habitat	1	1	300	meters	1000
39	Emplace Habitat	5	1	1	lg items	0.2
40	Anchor Habitat	4	1	4	points	1
41	Unload Airlock & TCS	10	1	2	lg items	0.2
42	Transport Airlock & TCS	1	1	300	meters	1000
43	Emplace TCS	1	1	1	med items	2
44	Anchor TCS	4	1	4	points	1
45	Emplace Airlock	5	1	1	lg item	0.2
46	Connect Airlock	2	1	8	points	4
47	Anchor Airlock	4	1	4	points	1
48	Emplace Tent	2	1	4	med items	2
49	Anchor Tent	4	1	4	points	1

Table B1. Quantities of Work for Base Initialization Construction Project (Page 2 of 3)

BASE INITIALIZATION						
February 2004 - June 2004						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
50	Inspect Habitat	3	1	10	points	4
51	Test Habitat	3	1	10	systems	4
52	Final Prep/Cleanup	1	1	250	square meters	250
53	**Utilities**		0			
54	**Install Power Cable**		0			
55	Survey Cable Trench	1	1	4	points	12
56	*Dig Cable Trench*		0			
57	Excavate Trench	2	1	6.25	cubic meters	3
58	Remove Sml Rocks	1	1	0.625	pieces	4
59	Remove Lg Rocks	1	1	0.0625	pieces	0.25
60	Install Cables	1	1	100	meters	500
61	Cover Cables	1	1	12.5	cubic meters	100
62	Connect Cables	1	1	4	connections	4
63	Inspect Cables	1	1	4	points	4
64	Final Prep/Cleanup	1	1	250	square meters	250
65	**TCS Piping**		0			
66	Survey Trench	1	1	3	points	12
67	*Excavate Cab Trn*		0			
68	Dig Piping Trench	1	1	3.125	cubic meters	3
69	Remove Sml Rocks	1	1	0.3125	pieces	4
70	Remove Lg Rocks	1	1	0.03125	pieces	0.25
71	Install Piping	1	1	50	meters	100
72	Cover Trench	1	1	3.125	cubic meters	6
73	Connect Piping	1	1	4	connections	4
74	Inspect Piping	1	1	4	points	4
75	Final Prep/Cleanup	1	1	250	square meters	250
76	Test All Systems	8	1	30	systems	4
77	Repair/Startup	14	1	7	systems	0.5
78	**Stock Hab**		0			
79	Xport Supplies	1	1	250	meters	1000
80	Ingress Supplies	49	1	65	sml items	1.33
81	Stow Supplies	16	1	65	sml items	4
82	**Launch/Land Area**		0			
83	Survey L/L Area	2	1	20	points	12
84	*L/L Area Surface Preparation*		0			
85	Level L/L Area	192	1	577	cubic meters	3
86	Remove Sml Rocks	14	1	58	pieces	4
87	Remove Lg Rocks	23	1	6	pieces	0.25
88	Blast Barriers	60	1	180	cubic meters	3
89	Anchor Pad Marke	1	1	1	points	1
90	Anchor Nav Beacon	3	1	3	points	1
91	**Science Site**		0			
92	Survey Science Site	1	1	12	points	12
93	*Surface Preparation*		0			
94	Level Site	20	1	60	cubic meters	3
95	Remove Small Rocks	1	1	0.6	pieces	4
96	Remove Large Rocks	1	1	0.06	pieces	0.25
97	*Cable*		0			

Table B1. Quantities of Work for Base Initialization Construction Project (Page 3 of 3)

BASE INITIALIZATION						
February 2004 - June 2004						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
98	Survey Cable Route	1	1	17	points	12
99	*Trench*		0			
100	Dig Trench	2	1	4.6875	cubic meters	3
101	Remove Small Rocks	1	1	0.04688	pieces	4
102	Remove Large Rocks	1	1	0.00469	pieces	4
103	Lay Cable	1	1	500	meters	500
104	Cover Cable	5	1	31.25	cubic meters	6
105	Connect Cable	1	1	4	points	4
106	Emplace Solar Observatory	2	1	3	med items	2
107	Inspect Solar Observatory	1	1	4	points	4
108	Test Solar Observatory	1	1	4	systems	4
109	Emplace Geophysical Station	1	1	5	sml items	4
110	Inspect Geophysical Station	2	1	6	points	4
111	Test Geophysical Station	2	1	6	systems	4
112	Final Prep/Cleanup	1	1	250	square meters	250
113	**LLOX Demo**		0			
114	Install LLOX Demo	2	1	4	med items	2
115	Lay Power Cables	1	1	100	meters	500
116	Connect Cables	1	1	4	connections	4
117	Inspect LLOX Demo	1	1	4	points	4
118	Test LLOX Demo	1	1	4	systems	4
119	Final Prep/Cleanup	1	1	250	square meters	250

Table B2. Quantities of Work for Logistics and Site Preparation, July 2004 (page 1 of 2)

LOGISTICS & SITE PREPARATION						
July 2004 - December 2004						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	**Receive Cargo**		0			
2	Offload Rover	1	1	1	med items	2
3	Test Rover	1	1	4	systems	4
4	Offload Lander	20	1	4	lg items	0.2
5	Transport All	1	1	300	meters	1000
6	**Supplies**		0			
7	Ingress Supplies	50	1	66	sml items	1.33
8	Stow Supplies	17	1	66	sml items	4
9	**PVA-RFC #2**		0			
10	Survey PVA/RFC	1	1	12	points	12
11	*Surface Preparation*		0			
12	Level PVA/RFC Site	20	1	60	cubic meters	3
13	Remove Sml Rocks	2	1	6	pieces	4
14	Remove Lg Rocks	2	1	0.6	pieces	0.25
15	Emplace RFC	5	1	1	lg items	0.2
16	Emplace PVA	2	1	4	med items	2
17	Connect PVA	2	1	8	points	4
18	Connect PVA/RFC	1	1	4	points	4
19	Inspect PVA/RFC	2	1	8	points	4
20	Test PVA/RFC	1	1	4	systems	4
21	Repair/Startup	2	1	1	system	0.5
22	Final Prep/Cleanup	1	1	250	square meters	250
23	**Comm Equip**		0			
24	Emplace Comm Equip	2	1	4	med items	2
25	Inspect Comm Equip	1	1	4	points	4
26	Test Comm Equip	1	1	4	systems	4
27	*Node*		0			
28	Emplace Node	5	1	1	lg items	0.2
29	Connect Node	2	1	8	points	4
30	Anchor Node	4	1	4	points	1
31	Inspect Node	2	1	8	points	4
32	Test Node	1	1	4	systems	4
33	Repair/Startup	1	1	1	systems	0.5
34	**Prep Next Phase**		0			
35	**PVA #3 Prep**		0			
36	Survey Site for PVA #3	1	1	12	points	12
37	*Surface Preparation*		0			
38	Level PVA #3 Site	20	1	60	cubic meters	3
39	Remove Sml Rocks	2	1	6	pieces	4
40	Remove Lg Rocks	2	1	0.6	pieces	0.25
41	**Opt Tel #1 Prep**		0			
42	Survey Site for Opt Tel #1	1	1	12	points	12
43	*Surface Preparation*		0			
44	Level Site for Tel #1	5	1	15	cubic meters	3
45	Remove Sml Rocks	1	1	1.5	pieces	4
46	Remove Lg Rocks	1	1	0.15	pieces	0.25
47	**MERI Prep**		0			
48	Survey Site for MERI	2	1	20	points	12

Table B2. Quantities of Work for Logistics and Site Preparation, July 2004 (page 2 of 2)

LOGISTICS & SITE PREPARATION						
July 2004 - December 2004						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
49	*Surface Preparation*		0			
50	Level MERI Site	5	1	15	cubic meters	3
51	Remove Sml Rocks	1	1	1.5	pieces	4
52	Remove Lg Rocks	1	1	0.15	pieces	0.25
53	**Hab Area Prep**		0			
54	Survey Hab Area	3	1	36	points	12
55	*Surface Preparation*		0			
56	Level Hab Site	500	1	1500	cubic meters	3
57	Remove Sml Rocks	38	1	150	pieces	4
58	Remove Lg Rocks	60	1	15	pieces	0.25
59	**Hab Area Roads**		0			
60	Survey Roads	6	1	67	points	12
61	*Surface Preparation*		0			
62	Level Roads	167	1	500	cubic meters	3
63	Remove Sml Rocks	13	1	50	pieces	4
64	Remove Lg Rocks	20	1	5	pieces	0.25

Table B3. Quantities of Work for Logistics and Site Preparation, January 2005 (page 1 of 2)

LOGISTICS & SITE PREPARATION						
Jan[illegible]ry 2005 - June 2005						
FY[illegible] Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	**Activate Equipment**		0			
2	Unload Unpressurized Rover	1	1	1	med items	2
3	Test Unpressurized Rover	1	1	4	systems	4
4	**Offload Balance**		0			
5	Lg Items	10	1	2	lg items	0.2
6	Med Items	3	1	6	med items	2
7	Transport Cargo	1	1	300	meters	4000
8	Ingress Supplies	75	1	100	sml items	1.33
9	Stow Supplies	25	1	100	sml items	4
10	**Optical Tel #1 (OT1)**		0			
11	Emplace OT1	2	1	3	med items	2
12	Connect OT1	2	1	6	points	4
13	Anchor OT1	4	1	4	points	1
14	Test OT1	1	1	4	systems	4
15	Repair/Start Up	2	1	1	systems	0.5
16	**Install PVA**		0			
17	Emplace PVA #3	2	1	4	med items	2
18	Anchor PVA #3	4	1	4	points	1
19	Connect PVA #3	2	1	8	points	4
20	Inspect PVA #3	1	1	4	points	4
21	Test PVA #3	1	1	4	systems	4
22	Repair/Start up	2	1	1	systems	0.5
23	**Install Cable**		0			
24	Emplace Cables	1	1	10	meters	500
25	Connect Cables	2	1	8	points	4
26	Cover Cables	1	1	0.625	cubic meter	6
27	Install MERI		0			
28	Emplace MERI	2	1	4	med items	2
29	Anchor MERI	4	1	4	points	1
30	Connect MERI	1	1	4	points	4
31	Inspect MERI	1	1	4	points	4
32	Test MERI	2	1	8	systems	4
33	Repair/Start up	4	1	2	systems	0.5
34	Final Prep/Cleanup	1	1	50	square meters	250
35	**Prep next phase**		0			
36	**Monitoring Telescope #2 (MT2)**		0			
37	Survey MT2 Site	1	1	12	points	12
38	*Surface Preparation*		0			
39	Level MT2 Site	5	1	15	cubic meters	3
40	Remove Sml Rocks	1	1	1.5	Sml rocks	4
41	Remove Lg Rocks	1	1	0.15	Lg Rocks	0.25
42	**Earth Observatory (EO)**		0			
43	Survey EO Site	1	1	12	points	12
44	*Surface Preparation*		0			
45	Level EO Site	5	1	15	cubic meters	3
46	Remove Sml Rocks	1	1	1.5	Sml rocks	4
47	Remove Lg Rocks	1	1	0.15	Lg Rocks	0.25
48	Road to L/L Area		0			

Table B3. Quantities of Work for Logistics and Site Preparation, January 2005 (page 2 of 2)

LOGISTICS & SITE PREPARATION						
January 2005 - June 2005						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Durat. n Type	Quantity of Work	Units of Work	Productivity (units/hr)
49	Layout LL Road	28	1	333	points	12
50	*Surface Preparation*		0			
51	Level L/L Road	833	1	2500	cubic meters	3
52	Remove Sml Rocks	63	1	250	Sml rocks	4
53	Remove Lg Rocks	100	1	25	Lg Rocks	0.25

Table B4. Quantities of Work for Science and Site Preparation, July 2005 (page 1 of 2)

LOGISTICS & SITE PREPARATION						
July 2005 - December 2005						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	**Activate Equipment**		0			
2	Unload Pressurized Utility Vehicle (PUV)	5	1	1	lg item	0.2
3	Test PUV	2	1	8	systems	4
4	Unload Tunnel Ramp	5	1	1	lg item	0.2
5	Test Tunnel Ramp	1	1	4	systems	4
6	Unload Power Trailer	5	1	1	lg item	0.2
7	Test Power Trailer	1	1	4	systems	4
8	Unload Fuel Cell Power (FCP) Cart	5	1	1	lg item	0.2
9	Test FCP Cart	1	1	4	systems	4
10	Unload Thermal Control (TC) Carts	5	1	1	lg item	0.2
11	Test TC Carts	1	1	4	systems	4
12	Unload Lab Trailer	5	1	1	lg item	0.2
13	Unload Rover	1	1	1	med item	2
14	Test Rover	1	1	4	systems	4
15	Liq Plant/Tanks		0			
16	Emplace P/Tanks	1	1	1	med items	2
17	Test Plant/Tanks	1	1	4	systems	4
18	Emplace Tents	2	1	4	med items	2
19	Unload Balance		0			
20	Lg items	15	1	3	lg items	0.2
21	Med items	1	1	1	med items	2
22	Transport Bal	1	1	300	meters	1000
23	Telescopes		0			
24	Emplace Teles	3	1	6	med item	2
25	Anchor Tele	8	1	8	points	1
26	Connect	2	1	8	points	4
27	Test Telescopes	2	1	8	systems	4
28	Repair/Start up	4	1	2	systems	0.5
29	Final Prep	1	1	100	square meters	250
30	Lab Trailer		0			
31	Tranport Lab Trailer	1	1	300	meters	4000
32	Emplace Lab Tlr	5	1	1	lg item	0.2
33	Conn Lab Trailer	3	1	10	points	4
34	Test Lab Trailer	1	1	5	systems	4
35	Ingress Biomed Lab	28	1	37	items	1.33
36	Emplace Biomed Lab	9	1	37	items	4
37	Ingress Science Lab	9	1	12	items	1.33
38	Emplace Science Lab	3	1	12	items	4
39	Earth Observatory (EO)		0			
40	Emplace EO	5	1	1	lg item	0.2
41	Anchor EO	4	1	4	points	1
42	Inspect EO	1	1	4	points	4
43	Test EO	1	1	4	systems	4
44	Repair/Start up	2	1	1	systems	40.5
45	Prep next phase		0			
46	SP-100 Prep		0			
47	Layout SP-100	1	1	12	points	12
48	Surf Prep SP-100		0			
49	Level	9	1	26.4938	cubic meters	3

Table B4. Quantities of Work for Science and Site Preparation, July 2005 (page 2 of 2)

LOGISTICS & SITE PREPARATION						
July 2005 - December 2005						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
50	Remove Sml Rocks	1	1	2.64938	sml rocks	4
51	Remove Lg Rocks	1	1	0.26494	lg rocks	0.25
52	Excavate		0			
53	Dig Hole	8	1	24	cubic meters	3
54	Remove Sml Rocks	1	1	2.4	sml rocks	4
55	Remove Lg Rocks	1	1	0.24	lg rocks	0.25
56	Cable for SP 100		0			
57	Layout Cab SP100	1	1	17	points	12
58	Dig Trench		0			
59	Trench	10	1	31.25	cubic meters	3
60	Remove Sml Rocks	1	1	3.125	sml rocks	4
61	Remove Lg Rocks	1	1	0.3125	lg rocks	0.25
62	Road To Nuclear Plants		0			
63	Layout	6	1	67	points	12
64	Surface Prep		0			
65	Level	167	1	500	cubic meters	3
66	Remove Lg Rocks	13	1	50	sl rocks	4
67	Remove Sml Rocks	20	1	5	lg rocks	0.25
68	LL Area		0			
69	Layout	5	1	60	points	12
70	Surface Prep		0			
71	Level	144	1	432.731	cubic mters	3
72	Remove Sml Rocks	11	1	43.2731	sml rocks	4
73	Remove Lg Rocks	17	1	4.32731	lg rocks	0.25
74	Blast Barriers	220	1	660	cubic meters	3

Table B5. Quantities of Work for Base Construction, January to June, 2006

SP-100 INSTALLATION & SITE PREPARATION FOR INFLATABLE HABITAT						
January 2006 to June 2006						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	Unload Lander	10	1	2	lg items	0.2
2	Xport to Base	5	1	5000	meters	1000
3	Ingress Consumables	84	1	112	sml items	1.33
4	Stow Consumables	27	1	108	sml items	4
5	Emplace Science Resupply	1	1	4	sml items	4
6	**SP-100**		0			
7	Emplace SP-100	5	1	1	Lg item	0.2
8	Emplace Cable	1	1	500	meters	500
9	Cover Trench	5	1	31.25	Cubic meters	6
10	Connect SP-100	1	1	5	points	4
11	Inspect SP-100	3	1	10	points	4
12	Test SP-100	3	1	10	systems	4
13	Repair/Start up	4	1	2	systems	0.5
14	Final Prep/Cleanup	1	1	250	square meters	250
15	**Prep Next Phase**		0			
16	**Inf Hab Prep**		0			
17	Layout Inf Hab	1	1	12	points	12
18	Excavate Inf Hab	67	1	2000	cubic meters	3
19	Remove Sml Rocks	50	1	200	sml rocks	4
20	Remove Lg Rocks	80	1	20	lb rocks	0.25
21	**IR Tele Prep**		0			
22	Layout IR Tele	1	1	12	points	12
23	*Surface Preparation*		0			
24	Level	5	1	15	cubic meters	3
25	Remove Sml Rocks	1	1	1.5	sml rocks	4
26	Remove Lg Rocks	1	1	0.15	lg rocks	0.25
27	**UV Tele Prep**		0			
28	Layout UV Telescope	1	1	12	points	12
29	*Surface Preparation*		0			
30	Level	5	1	15	cubic meters	3
31	Remove Sml Rocks	1	1	1.5	sml rocks	4
32	Remove Lg Rocks	1	1	0.15	lg rocks	0.25
33	**Rd to ISRU Area**		0			
34	Layout	2	1	24	points	12
35	*Surface Preparation*		0			
36	Level	5	1	15	cubic meters	3
37	Remove Sml Rocks	1	1	1.5	sml rocks	4
38	Remove Lg Rocks	1	1	0.15	lg rocks	0.25

Table B6. Quantities of Work for Base Construciton, July to December, 2006

INSTALLATION OF INFLATABLE & SCIENCE INFRASTRUCTURE						
July 2006 to December 2006						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	**Inf Hab**		0			
2	Offload Inflatable Hab	5	1	1	lg items	0.2
3	Transport Inflatable Hab	5	1	5000	meters	1000
4	Emplace Foundation	1	1	1	med item	2
5	Anchor Foundation		1	8	points	1
6	Emplace Inf Hab	5	1	1	lg item	0.2
7	Inflate Hab	20	1	10	systems	0.5
8	Conn to Foundation	2	1	6	points	4
9	Connect Power	1	1	4	points	4
10	Offload Tunnel	5	1	1	lg item	0.2
11	Transport Tunnel	5	1	5000	meters	1000
12	Emplace Tunnel	5	1	1	lg item	0.2
13	Connect Tunnel	2	1	6	points	4
14	Anchor Tunnel	4	1	4	points	1
15	Inspect Hab/Tunnel	3	1	10	points	4
16	Test Hab/Tunnel	1	1	4	sysetms	4
17	Repair/Startup	2	1	1	systems	0.5
18	Backfill Hab	167	1	1000	cubic meters	6
19	**IR Telescope (IRT)**		0			
20	Emplace IRT	2	1	4	med items	2
21	Connect IRT	2	1	6	points	4
22	Anchor IRT	4	1	4	points	1
23	Inspect IRT	1	1	4	points	4
24	Test IRT	1	1	4	systems	4
25	Repair/Startup	2	1	1	systems	0.5
26	Final Prep	1	1	50	square meters	250
27	**UV Telescope (UVT)**		0			
28	Emplace UVT	2	1	4	med item	2
29	Connect	2	1	6	points	4
30	Anchor	4	1	4	points	1
31	Inspect	1	1	4	points	4
32	Test UVT	1	1	4	systems	4
33	Repair/Startup	2	1	1	system	0.5
34	Final Prep	1	1	50	square meters	250
35	**Road, Nuclear Plants to ISRU**		0			
36	Survey	4	1	50	points	12
37	*Surface Preparation*		0			
38	Level	167	1	500	cubic meters	3
39	Remove Sml Rocks	13	1	50	sml rocks	4
40	Remove Lg Rocks	20	1	5	lg rocks	0.25

Table B7. Quantities of Work for Base Construction, January to June, 2007

Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
INSTALLATION OF INFLATABLE						
January 2007 to June 2007						
FY89 Lunar Evolution Case Study						
1	Offload Lander	5	1	1	lg item	0.2
2	Transport Cargo	5	1	5000	meters	1000
3	Stow Consumables	25	1	100	sml items	4
4	**Thermal Control System (TCS), Inf.**		0			
5	Offload TCS	5	1	1	lg item	0.2
6	Xport TCS	20	1	5000	meters	1000
7	Emplace TCS (exterior)	5	1	1	lg item	0.2
8	Anchor TCS (exterior)	8	1	8	points	1
9	TCS Ingress	11	1	14	items	1.33
10	Emplace TCS (interior)	4	1	14	sml items	4
11	**Piping Trench**		0			
12	Dig Trench	2	1	6.25	cubic meter	3
13	Remove sml rocks	1	1	0.625	sml rocks	4
14	Remove lg rocks	1	1	0.0625	lg rocks	0.25
15	Emplace Piping	1	1	100	meters	100
16	Cover Trench	1	1	6.25	cubic meters	6
17	Connect Piping	1	1	4	points	4
18	Inspect TCS	10	1	38	points	4
19	Test TCS	29	1	116	systems	4
20	Repair/Startup	58	1	29	systems	0.5
21	**Road, ISRU To L/L**		0			
22	Survey	3	1	40	points	12
23	*Surface Preparation*		0			
24	Level	667	1	2000	cubic meters	3
25	Remove Sml Rocks	50	1	200	sml rocks	4
26	Remove Lg Rocks	80	1	20	lg rocks	0.25

Table B8. Quantities of Work for Base Construction, July to December, 2007

INSTALLATION OF INFLATABLE						
July 2007 to December 2007						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	**Activate Equipment**		0			
2	Offload Power Trailer (PT)	5	1	1	lg item	0.2
3	Test PT	1	1	4	systems	4
4	Offload PUV #2	5	1	1	lg item	0.2
5	Test PUV #2	2	1	8	systems	4
6	Offload Bal	15	1	3	lg item	0.2
9	Export Balance	5	1	5000	meters	1000
10	**RLSS**		0			
11	Install RLSS ext	25	1	5	lg items	0.2
12	Inspect RLSS ext	25	1	100	points	4
13	RLSS Ingress	44	1	59	items	1.33
14	Install RLSS int	15	1	59	sml items	4
15	Inspect int	25	1	100	points	4
16	Test RLSS	100	1	400	systems	4
17	Repair/Startup	200	1	100	systems	0.5
18	**Outfitting**		0			
19	Outfitting Ingr	67	1	89	items	1.33
20	Inst Outfitting	22	1	89	sml items	4
21	Test Outfitting	11	1	45	systems	4
22	Repair/Start Up	24	1	12	systems	0.5
23	**Opt Tel #2**		0			
24	Layout	1	1	12	points	12
25	*Surface Preparation*		0			
26	Level	5	1	15	cubic mters	3
27	Remove Sml Rocks	1	1	1.5	sml rocks	4
28	Remove Lg Rocks	1	1	0.15	lg rocks	0.25
29	Emplace Opt Tel2	1	1	1	med item	2
30	Anchor OT #2	4	1	4	points	1
31	Inspect OT #2	2	1	6	points	4
32	Test OT #2	1	1		systems	4
33	Repair/StUp OT2	2	1		systems	0.5
34	Cover Hab	567	1	1700	cubic meters	3

Table B9. Quantities of Work for Base Construction, January to June, 2008

LOGISTICS & SCIENCE INSTALLATION						
January 2008 to June 2008						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	Offload Lander	5	1	1	lg item	0.2
2	Xport Cargo	5	1	5000	meters	1000
3	Stow Consumables	25	1	100	sml items	4
4	**Install Optical Telescope #3 (OT3)**		0			
5	Survey Site for OT3	1	1	12	points	12
6	*Surface Preparation*		0			
7	Level OT3 Site	5	1	15	cubic meters	3
8	Remove Sml Rocks	1	1	1.5	sml rocks	4
9	Remove Lg Rocks	1	1	0.15	lg rocks	0.25
10	Emplace OT3	1	1	1	med item	2
11	Anchor OT3	4	1	4	points	1
12	Inspect OT3	2	1	6	points	4
13	Test OT3	1	1	4	systems	4
14	Repair/Startup OT3	2	1	1	systems	0.5

Table B10. Quantities of Work for Base Construction, July to December 2008

LAUNCH/LANDING FACILITY & COMMUNICATIONS INSTALLATION						
July 2008 to December 2008						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	**Launch/Landing Facility Additions**		0			
2	Offload Additions	25	1	5	lg items	0.2
3	Emplace Additions	25	1	5	lg items	0.2
4	Test Additions	3	1	10	systems	4
5	**Install Communications Tower**		0			
6	Offload Tower	1	1	1	med items	2
7	Transport Tower	1	1	5000	meters	4000
8	Emplace Foundation	2	1	4	med items	2
9	Anchor Foundation	4	1	4	points	1
10	Emplace Tower	1	1	1	med item	2
11	Anchor Tower	4	1	4	points	1
12	Connect Tower	1	1	4	points	4
13	Test Tower	1	1	4	systems	4
14	Repair/Startup Tower	2	1	1	systems	0.5

Table B11. Quantities of Work for Base Construction, January to June, 2009

CONSTRUCTIBLE NUCLEAR PLANT (Site Preparation)						
January 2009 to June 2009						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	Offload Lander	10	1	2	lg items	0.2
2	Transport Cargo	5	1	5000	meters	1000
3	Stow Consumables	25	1	100	sml items	4
4	**Prep Next Phase**		0			
5	**Nuclear Plant Site Preparation**		0			
6	Survey Plant Site	2	1	20	points	12
7	*Excavate*		0			
8	Dig pit	12	1	35	cubic meters	3
9	Remove sml rocks	1	1	4	sml rocks	4
10	Remove lg rocks	4	1	1	lg rocks	0.25
11	*Surface Preparation*		0			
12	Level Site	141	1	423.9	cubic meters	3
13	Remove sml Rocks	1	1	4	sml rocks	4
14	Remove Lg rocks	4	1	1	lg rocks	0.25
15	**PMAD Site Preparation**		0			
16	Survey PMAD Site	4	1	50	points	12
17	*Trench*		0			
18	Dig trench	15	1	43.75	cubic meter	3
19	Remove Sml Rocks	1	1	4	sml rocks	4
20	Remove lg rocks	4	1	1	lg rocks	0.25

Table B12. Quantities of Work for Base Construction, July to December, 2009

INSTALLATION OF CONSTRUCTIBLE NUCLEAR PLANT (CONT.)						
July 2009 to December 2009						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	**Consumables**		0			
2	Offload Consumables	5	1	1	lg item	0.2
3	Transport Consumables	5	1	5000	meters	1000
4	Ingress Consumables	81	1	108	sml items	1.33
5	Stow Consumables	27	1	108	sml items	4
6	**Install Nuclear Power Plant**		0			
7	Offload Plant	5	1	1	lg item	0.2
8	Transport Plant	6	1	6000	meters	1000
9	Emplace Bulkhead	5	1	1	large piece	0.2
10	Inspect Bulkhead	3	1	12	points	4
11	Backfill Pit	2	1	14	m^3	6
12	Inspect Pit	3	1	12	points	4
13	Emplace Reactor	5	1	1	large piece	0.2
14	Emplace I/O Manifolds	1	1	1	med piece	2
15	Connect I/O Manifolds	1	1	2	points	4
16	Emplace engine platforms	4	1	8	med pieces	2
17	Emplace engines	40	1	8	large pieces	0.2
18	Connect heat rejections pipes	4	1	16	points	4
19	Connect shunts	4	1	16	points	4
20	Connect converters	2	1	8	points	4
21	Inspect Connections	14	1	56	points	4
22	Emplace reflecting blanket	40	1	8	large pieces	0.2
23	Emplace panels	20	1	40	med pieces	2
24	Connect panels	10	1	40	points	4
25	Anchor radiators	48	1	48	points	1
26	Connect manifold	2	1	8	points	4
27	Emplace switching station	2	1	3	med piece	2
28	Emplace utilities	1	1	700	meters	500
29	Connect Utilities	2	1	8	points	4
30	Inspect Connections	9	1	35	points	4
31	Backfill Trench	7	1	43.75	cubic meters	6
32	Inspect Trench	9	1	35	points	4
33	Final Prep/Cleanup	[illegible]	[illegible]	140	square meters	250
34	Activate & Test Plant	8	1	32	systems	4
35	Repair/Startup Plant	16	1	8	systems	0.5

Table B13. Quantities of Work for Base Construction, January to June, 2010

INSTALLATION OF CONSTRUCTIBLE NUCLEAR PLANT (CONT.)						
July 2009 to December 2009						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	**Consumables**		0			
2	Offload Consumables	5	1	1	lg item	0.2
3	Transport Consumables	5	1	5000	meters	1000
4	Stow Consumables	25	1	100	sml items	4

Table B14. Quantities of Work for Lunar Base Construction, July to December, 2010 (page 1 of 2)

LLOX FACILITY & SCIENCE INSTALLATIONS						
July 2010 - December 2010						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	**Consumables**		0			
2	Offload Consumables	5	1	1	lg item	0.2
3	Transport Consumables	5	1	5000	meters	1000
4	Stow Consumables	25	1	100	sml items	4
5	**LLOX Facility**		0			
6	**LLOX Plant**		0			
7	Survey Site	2	1	20	points	12
8	*Surface Preparation*		0			
9	Level	3	1	10.05	cubic meters	3
10	Remove sml rocks	1	1	1.005	sml rocks	4
11	Remove lg rocks	1	1	0.1005	lg rocks	0.25
12	Offload	5	1	1	lg item	0.2
13	Transport	5	1	5000	meters	1000
14	Emplace	5	1	1	lg item	0.2
15	Anchor	3	1	3	points	1
16	**Install TCS**		0			
17	Emplace	5	1	1	lg item	0.2
18	Anchor	8	1	8	points	1
19	Connect	1	1	4	points	4
20	**Beneficiation Equipment**		0			
21	Offload	5	1	1	lg item	0.2
22	Emplace Lg Item	1	1	0	lg items	0.2
23	Emplace Med Item	2	1	3	med items	2
24	Emplace Sml Item	1	1	4	sml items	4
25	Inspect	3	1	10	points	4
26	Connect cables	2	1	6	points	4
27	**Storage Tanks**		0			
28	*Excavate*		0			
29	Dig	20	1	60	cubic meters	3
30	Remove sml Rocks	2	1	6	sml rocks	4
31	Remove Lg Rocks	2	1	0.6	lg rocks	0.25
32	Emplace Tanks	1	1	2	med items	2
33	Connect	2	1	8	points	4
34	Cover Tanks	5	1	30	cubic meters	6
35	**Install PMAD**		0			
36	Survey Site	3	1	35	points	12
37	*Trench*		0			
38	Dig trench	21	1	62.5	cubic meters	3
39	Remove sml rocks	2	1	6.25	sml rocks	4
40	Remove lg rocks	3	1	0.625	lg rocks	0.25
41	Emplace Cable	2	1	1000	meters	500
42	Cover Cable	10	1	62.5	cubic meters	6
43	Connect Cable	2	1	8	points	4
44	Inspect all systems	5	1	20	points	4
45	Activate/test	1	1	10	systems	4
46	Repair/start up	6	1	3	systems	0.5
47	Final prep/clean up	1	1	250	square meters	250
48	**Mining Equipment**		0			

Table B14. Quantities of Work for Lunar Base Construction, July to December, 2010 (page 2 of 2)

LLOX FACILITY & SCIENCE INSTALLATIONS						
July 2010 - December 2010						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
49	Offload	15	1	3	lg items	0.2
50	Transport	5	1	5000	meters	1000
51	Test	3	1	12	systems	4
52	Repair/Start up	6	1	3	systems	0.5
53	**Gamma Ray Telescope**		0			
54	Survey site	1	1	12	points	12
55	*Surface Preparation*		0			
56	Level	11	1	33.75	cubic meters	3
57	Remove sml rocks	1	1	3.375	sml rocks	4
58	Remove lg rocks	1	1	0.3375	lg rocks	0.25
59	Offload	10	1	2	Lg item	0.2
60	Transport	5	1	5000	meters	1000
61	Emplace	10	1	2	lg items	0.2
62	Anchor	6	1	6	points	1
63	Inspect	1	1	4	points	4
64	Test	1	1	4	systems	4
65	Repair/start up	2	1	1	systems	0.5

Table B15. Quantities of Work for Lunar Base Construction, January to July, 2011

RESUPPLY MISSION						
January 2011 - June 2011						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	**Consumables**		0			
2	Offload Consumables	5	1	1	lg item	0.2
3	Transport Consumables	5	1	5000	meters	1000
4	Stow Consumables	40	1	160	sml items	4

Table B16. Quantities of Work for Lunar Base Construction, July to December, 2011

SCIENCE & LABORATORY INSTALLATION						
July 2011 - December 2011						
FY89 Lunar Evolution Case Study						
Task ID	Task Name	Duration (hrs)	Duration Type	Quantity of Work	Units of Work	Productivity (units/hr)
1	**Pressurized Research Vehicle**		0			
2	Offload	5	1	1	lg item	0.2
3	Test	1	1	4	systems	4
4	Offload Balance	15	1	3	lg items	0.2
5	Transport Balance	5	1	5000	meters	1000
6	Stow Science Resupply	1	1	4	sml items	4
7	Ingress Lab Istruments	75	1	100	sml items	1.33
8	Install Lab Instruments	25	1	100	sml items	4
9	**X-Ray Telescope**		0			
10	Survey Site	1	1	12	points	12
11	*Surface Preparation*		0			
12	Level	5	1	15	cubic meters	3
13	Remove sml rocks	1	1	1.5	sml rocks	4
14	Remove Lg rocks	1	1	0.15	lg rocks	0.25
15	Trnsport	1	1	1000	meters	4000
16	Emplace	1	1	2	med items	2
17	Anchor	4	1	4	points	1
18	Inspect	1	1	4	points	4
19	Test	2	1	6	systems	4
20	Repair/startup	4	1	2	systems	0.5

APPENDIX C: CONSTRUCTION PROJECT SCHEDULES

The period from February 2004 to December 2011 of the FY89, the Lunar Evolution Case Study was divided into 16, 6-month project timeframes. Gantt charts of the activities to be performed during each project timeframe are presented in Figures C1 through C16. Many of the detailed tasks called out in the spreadsheets provided in Appendix B have been condensed into major tasks to provide an overview of the entire 6-month period on a single page. Four basic symbols are used in the figures to indicate the critical path of activities in the schedule. A key to the symbols is provided below.

	Non Critical		Finish Delay
	Critical	>>>>>	Float/Delay

The activities involving the handling of lunar regolith consume a large portion of the construction project schedules. Regolith-moving tasks such as leveling, excavation, and trenching are required for many of the site preparation activities, such as the surface preparation for a roadway between the nuclear power plant site and the In Situ Resource Utilization (ISRU) site shown in Figure C6. The removal of small and large boulders accompanies the regolith-moving tasks. The boulder removal operation will take place simultaneously with tasks such as leveling, but in the Gantt charts the boulder removal activity is shown to occur after the leveling task is over. This anomaly is the result of an imprecise networking of the tasks. The primary objective in linking the tasks was to account for the work being performed, rather than reflect a precise simulation of the operation required. A much more detailed subdivision of the tasks would be required to illustrate the interplay between leveling and rock removal that occurs when a single mobile work platform with attachments is being used to perform both functions.

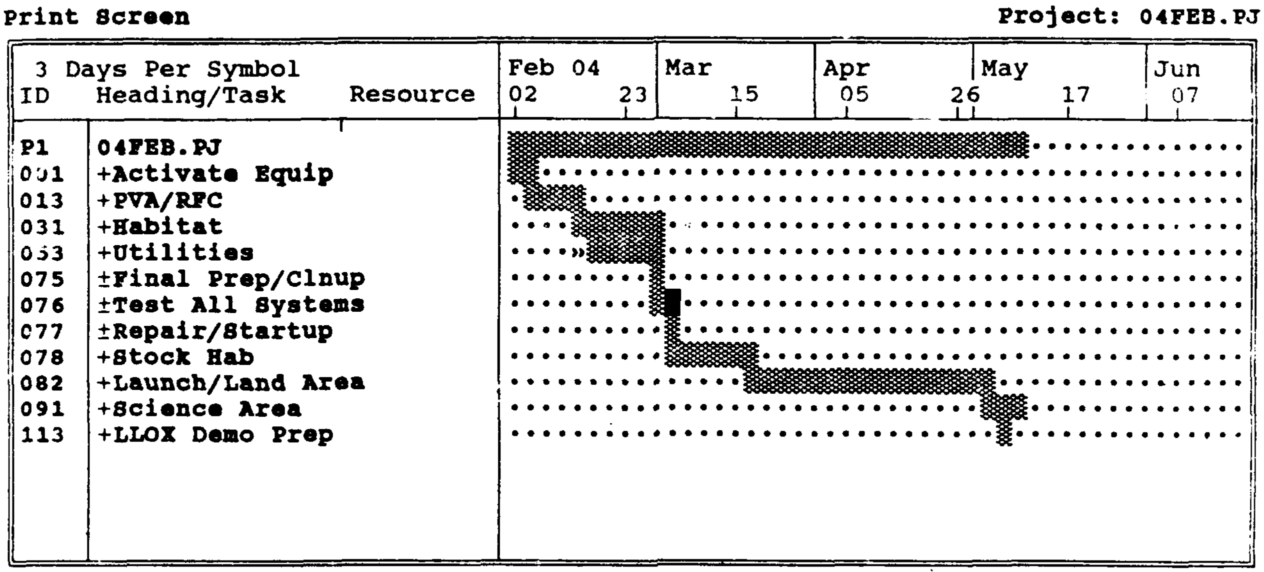

Figure C1. Gantt chart for base initialization construction project.

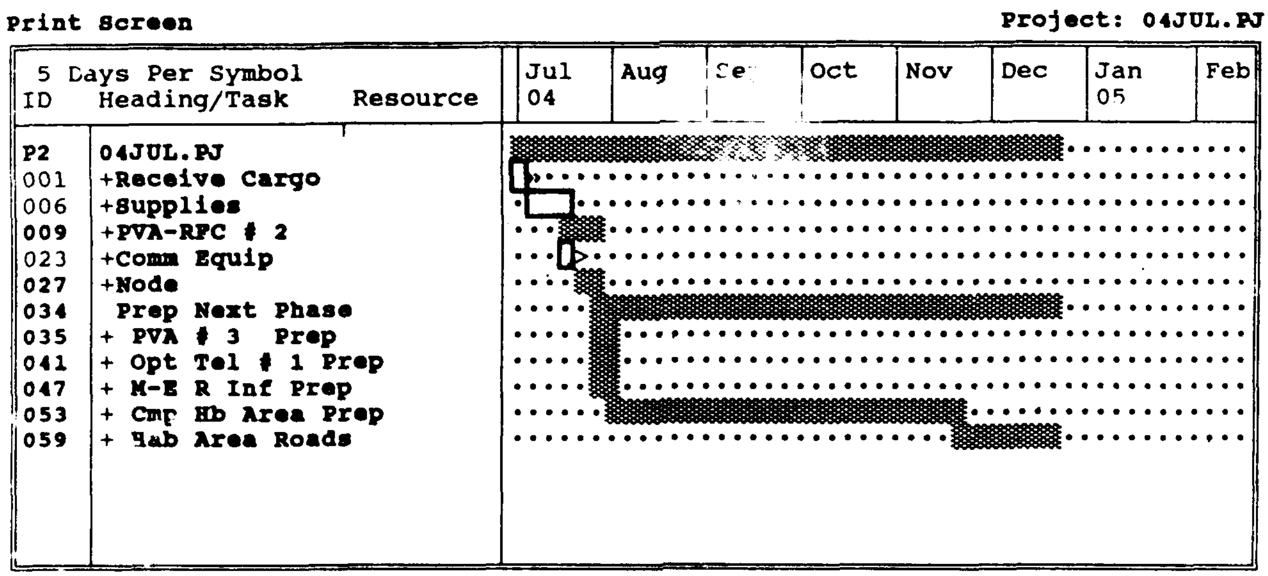

Figure C2. Gantt chart for lunar base construction, July to December, 2004.

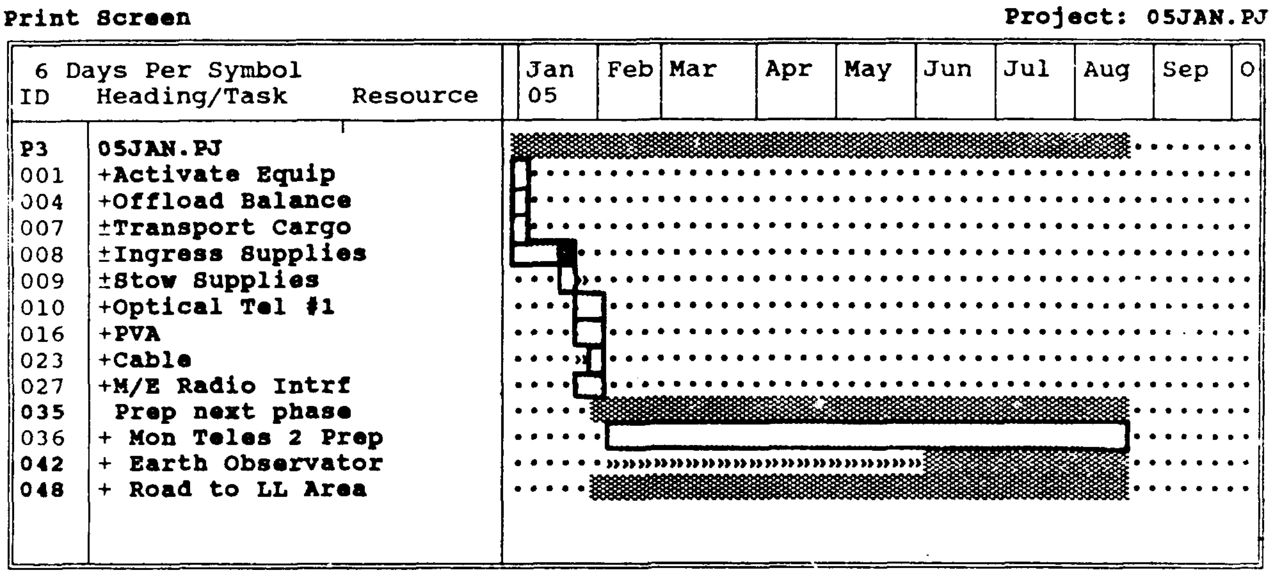

Figure C3. Gantt chart for lunar base construction, January to June, 2005.

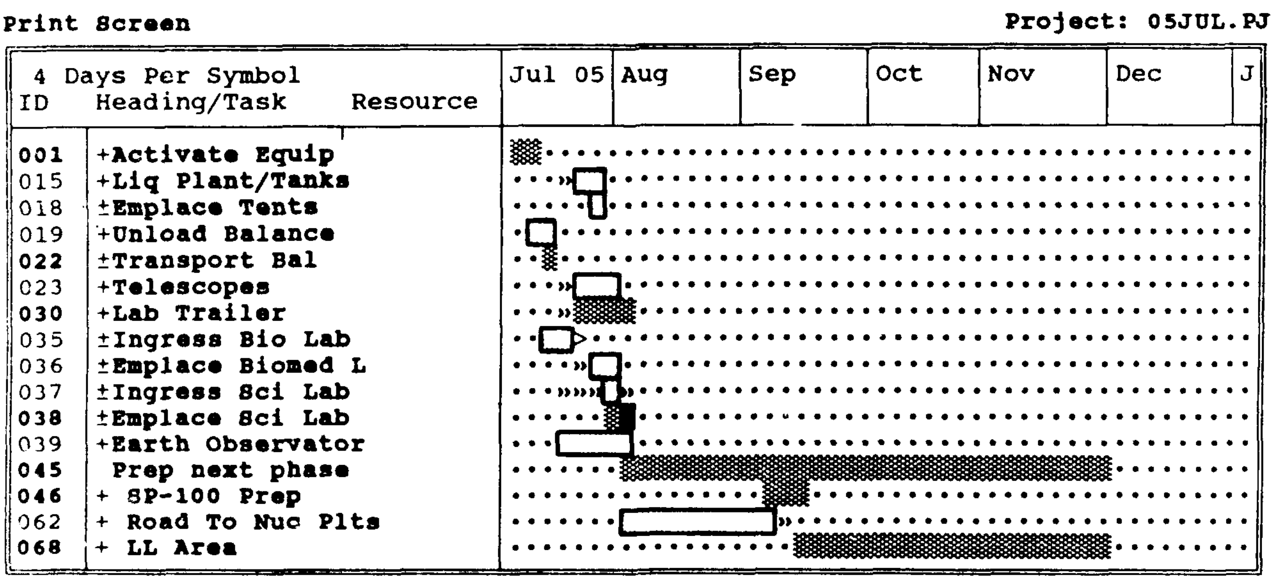

Figure C4. Gantt chart for lunar base construction, July to December, 2005

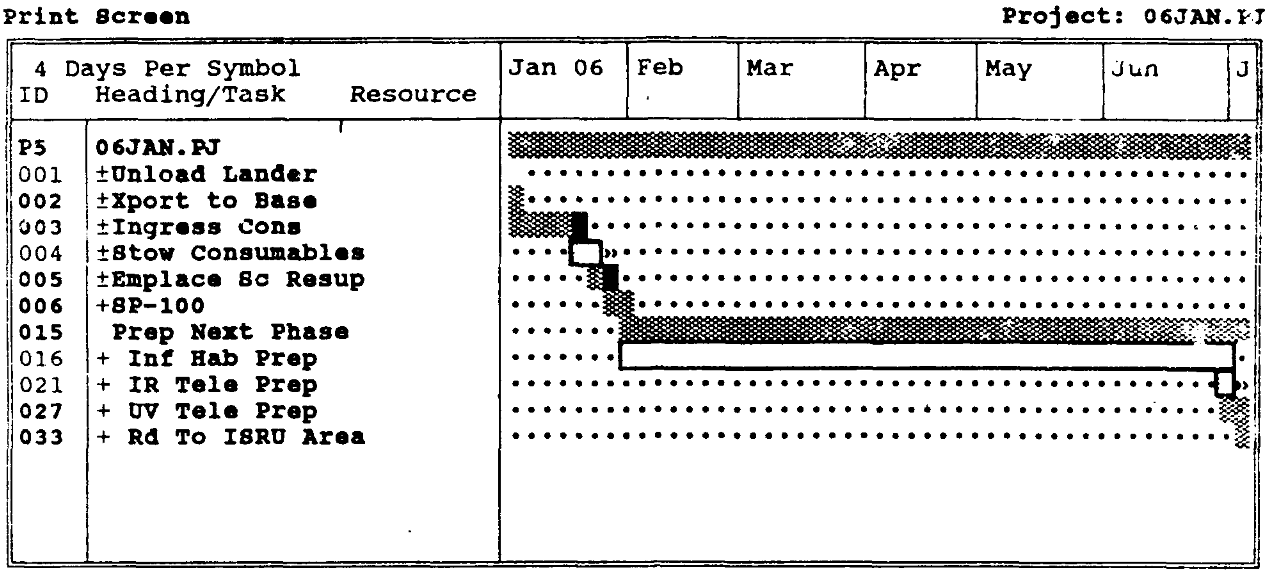

Figure C5. Gantt chart for lunar base construction, January to June, 2006.

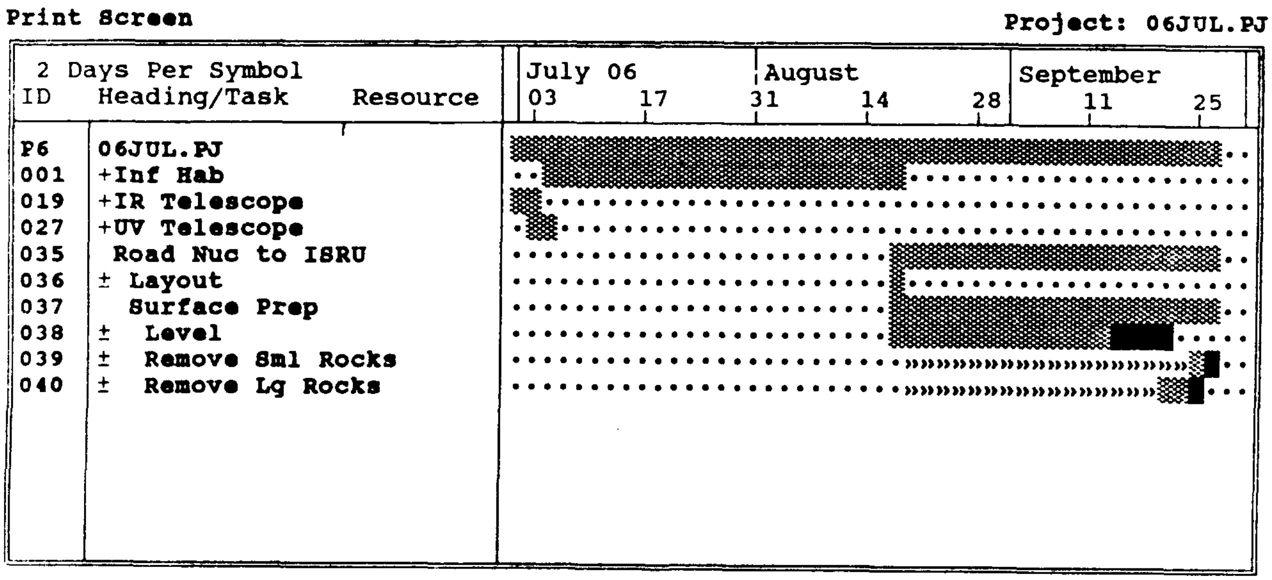

Figure C6. Gantt chart for lunar base construction, July to December, 2006.

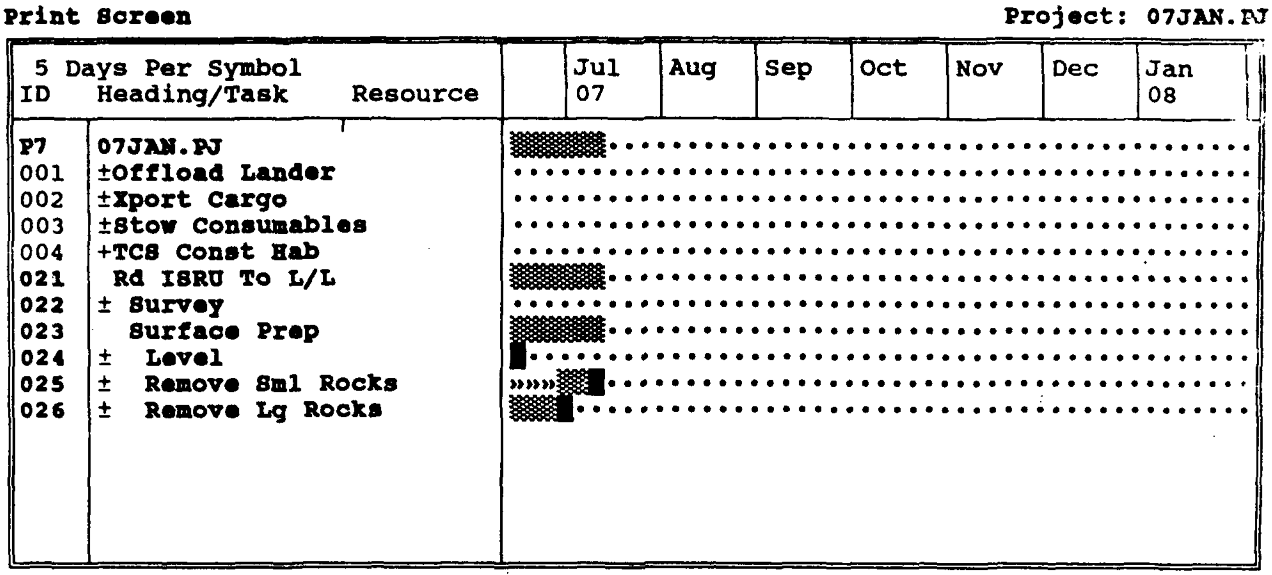

Figure C7. Gantt chart for lunar base construction, January to June, 2007.

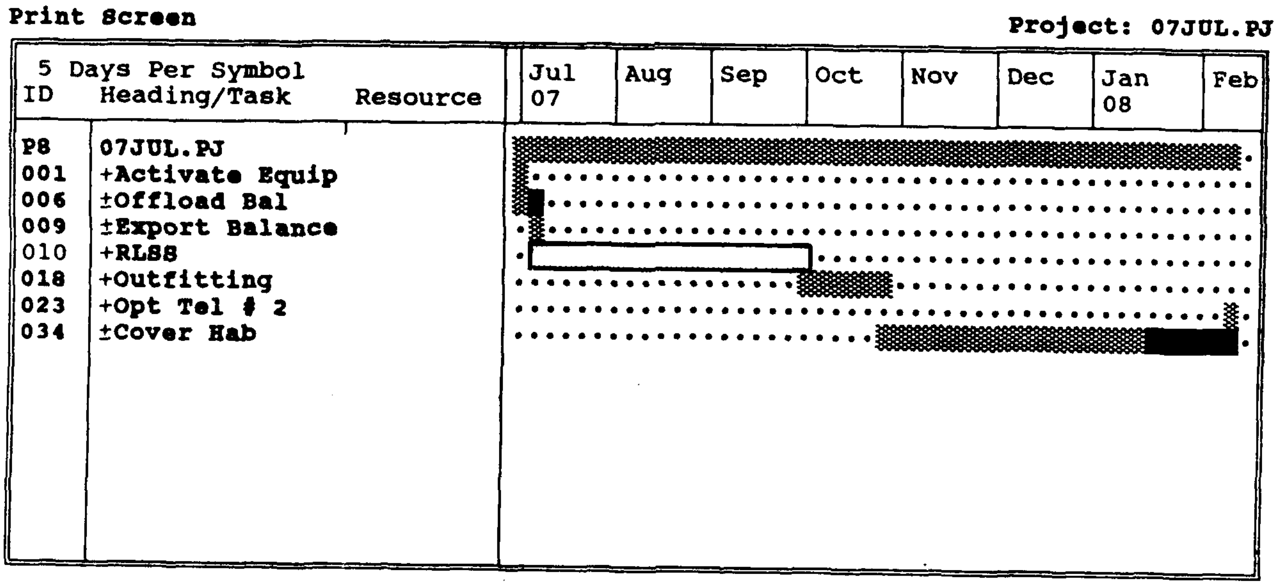

Figure C8. Gantt chart for lunar base construction, July to December, 2007.

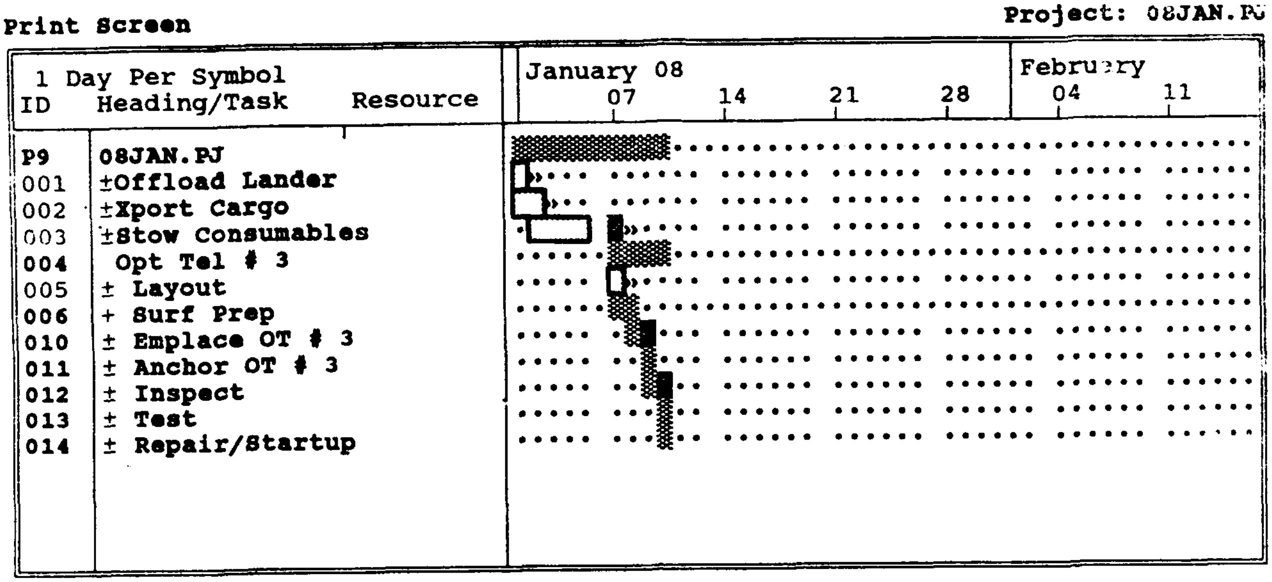

Figure C9. Gantt chart for lunar base construction, January to June, 2008.

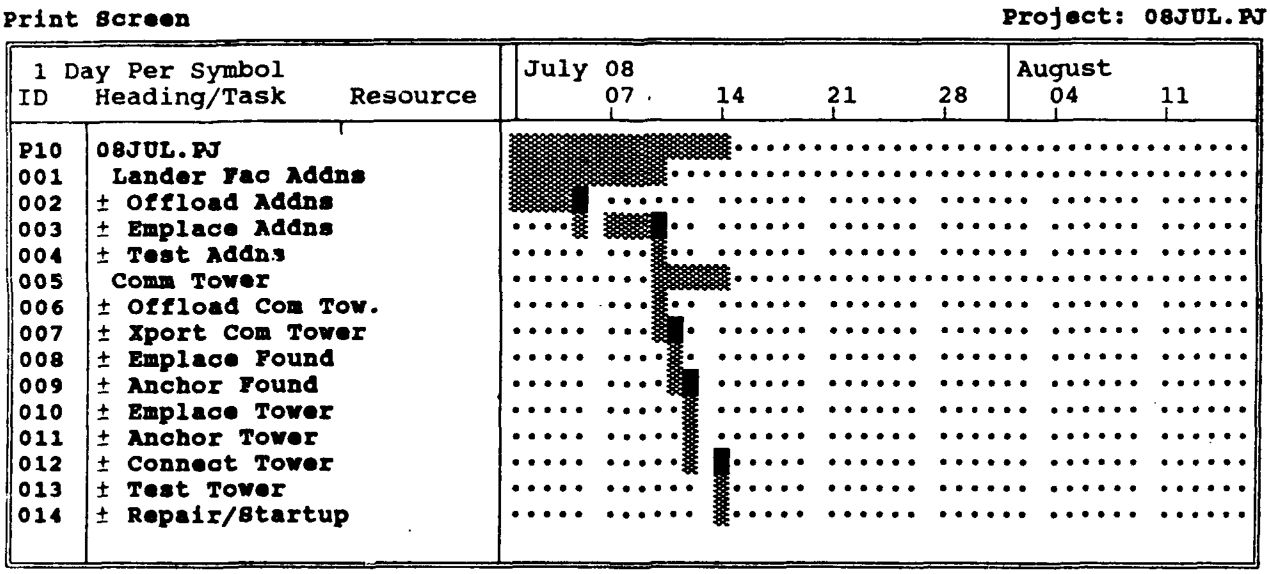

Figure C10. Gantt chart for lunar base construction, July to December, 2008.

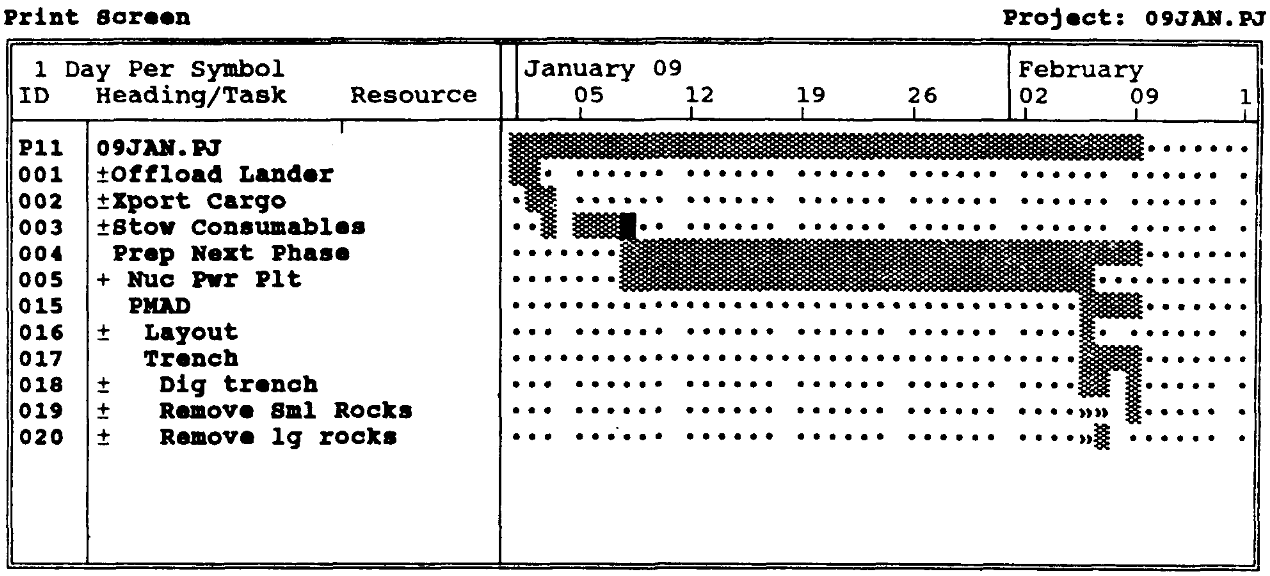

Figure C11. Gantt chart for lunar base construction, January to June, 2009.

Task Gantt **Project: 09JUL.PJ**
04-09-90 11:26a **Revision: 20**

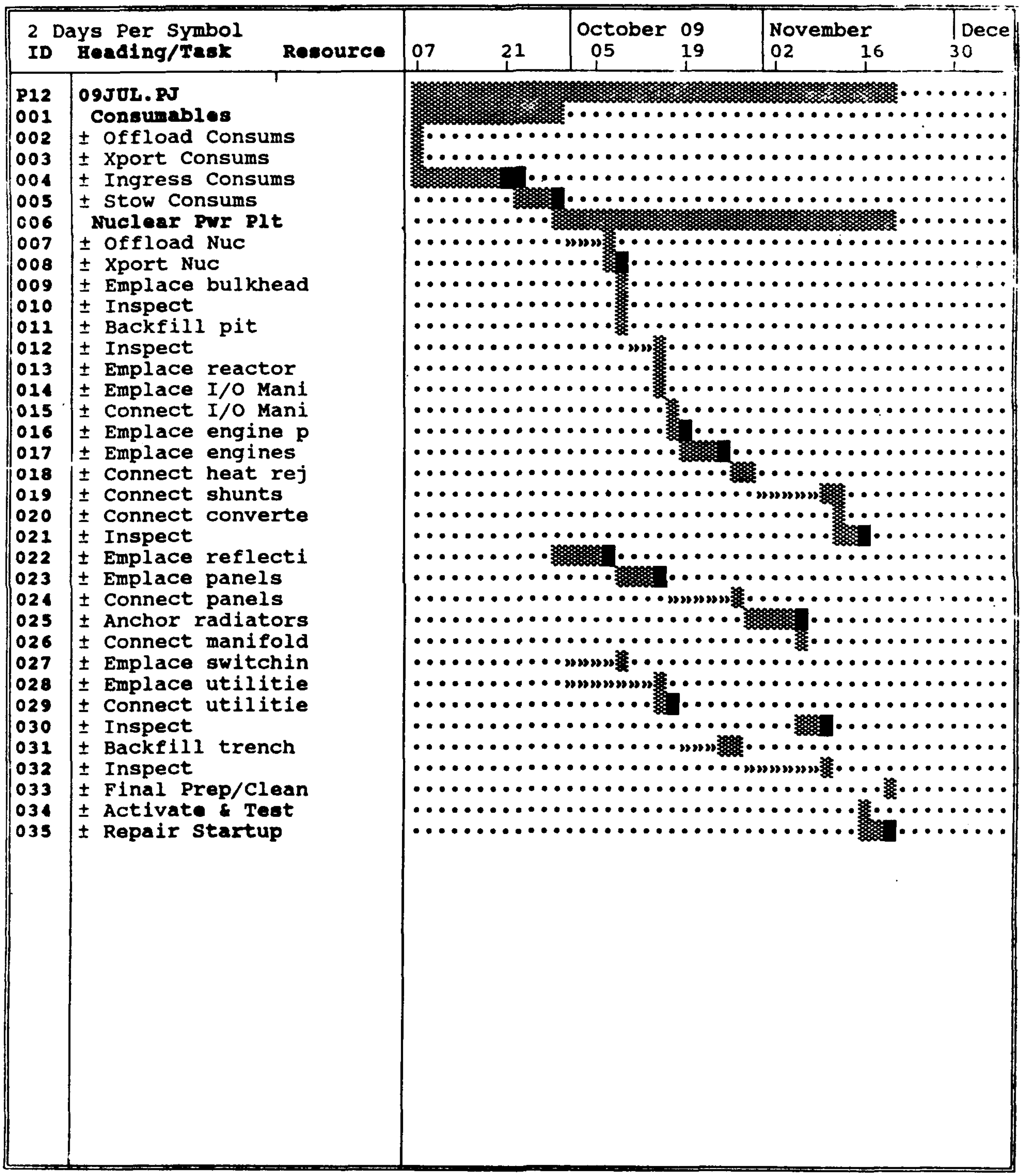

Figure C12. Gantt chart for lunar base construction, July to December, 2009.

Print Screen Project: 10JAN.PJ

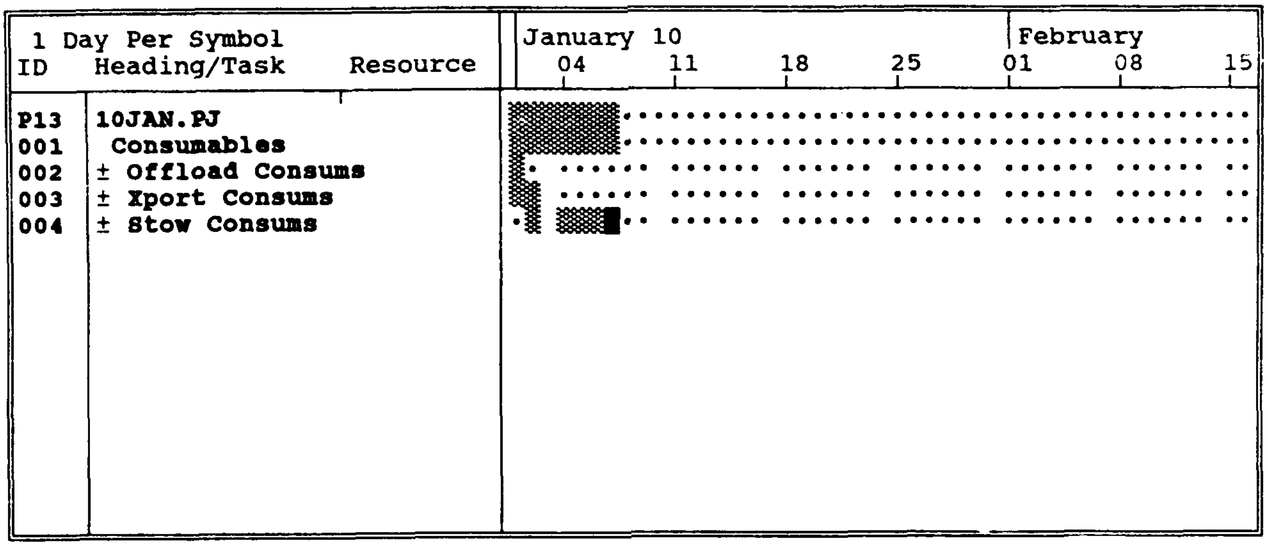

Figure C13. Gantt chart for lunar base construction, January to June, 2010.

Print Screen Project: 10JUL.PJ

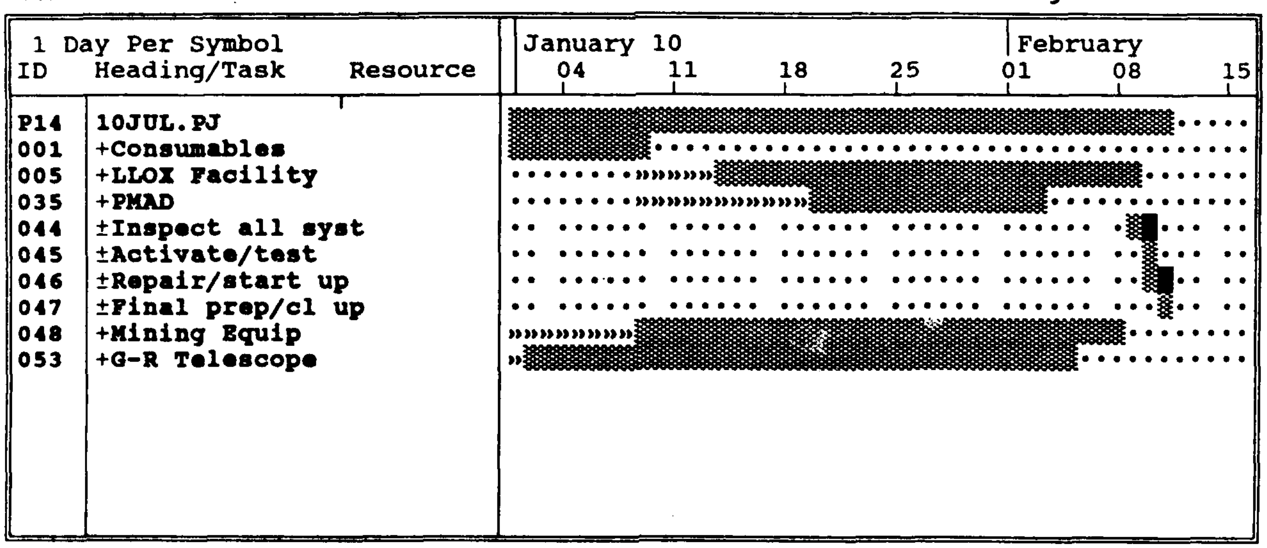

Figure C14. Gantt chart for lunar base construction, July to December, 2010.

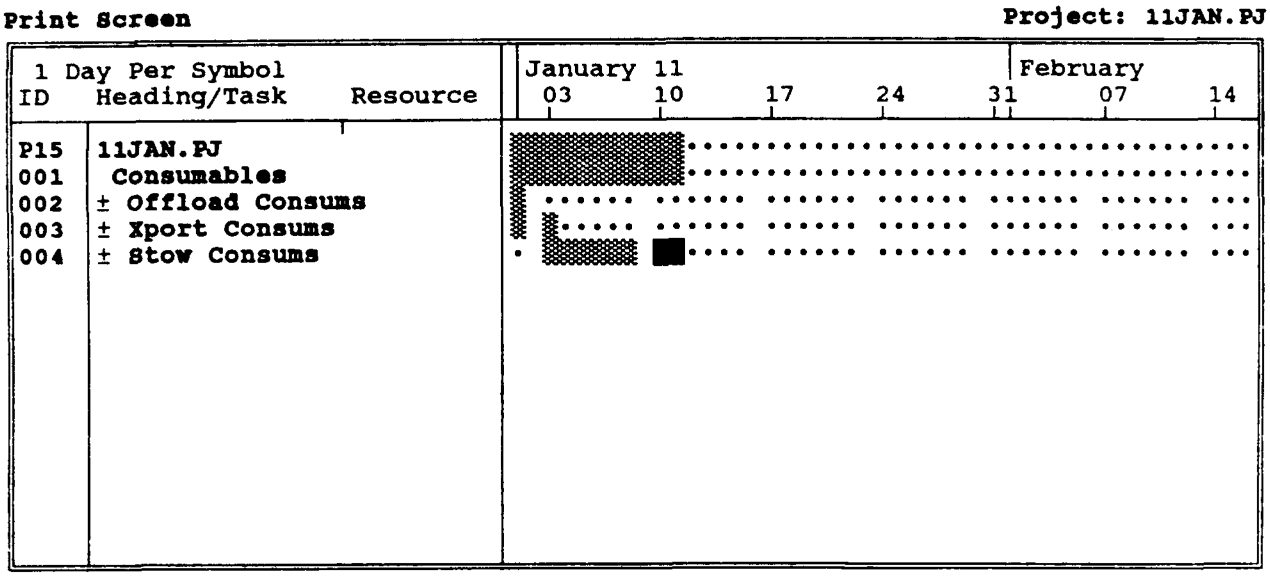

Figure C15. Gantt chart for lunar base construction, January to June, 2011.

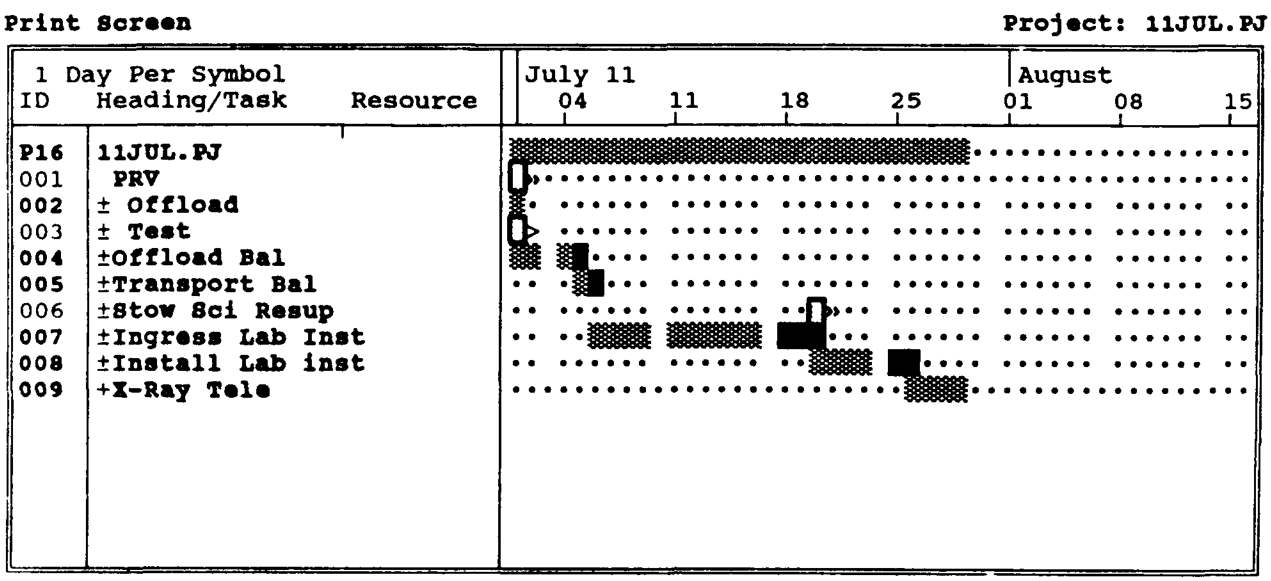

Figure C16. Gantt chart for lunar construction project, July to December, 2011.

ABBREVIATIONS

A&R	automation and robotics
ASCE	American Society of Civil Engineers
EEI	Eagle Engineering, Inc.
EVA	extravehicular activity
FY	fiscal year
GCR	galactic cosmic radiation
HEI	Human Exploration Initiative
ISRU	in situ resource utilization
IVA	intravehicular activity
JSC	Johnson Space Center
kw	kilowatt
kwe	kilowatt electric
LECS	Lunar Evolution Case Study
LLOX	liquified lunar oxygen
MEP	mobile equipment platform
MWP	mobile work platform
NASA	National Aeronautics and Space Administration
OEXP	NASA Office of Exploration
PVA	photovoltaic array
QOW	quantity of work
SSF	Space Station Freedom
SUPR	Symbolic Unified Project Representation
TCS	thermal control system
USACE	U.S. Army Corps of Engineers
USACERL	U.S. Army Construction Engineering Research Laboratory
VLF	very low frequency (radio telescope)

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